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Abstract

This paper employs multiple regression analysis to evaluate the effectiveness of yield-raising techniques available to medieval farm managers (reeves) using a panel dataset of 49 manors held by the Bishop of Winchester from 1349-70. There are three main interesting findings. First, annual weather variation, modelled with climate reconstructions, was highly significant in explaining annual yield variation in wheat, barley, and oat yields, though the weather influenced each grain differently. Second, there is evidence that planting leguminous fodder crops and livestock stocking rates had small or even negative effects on grain yields. Finally, there is indirect evidence that reeves responded to economic incentives in allocating labour inputs such as manuring, weeding, harvesting, and gleaning among their crops, giving them a small ability to adjust their output based on economic incentives. These findings complicate our understanding of the agricultural revolution. The ineffectiveness of short-run yield-raising strategies employed in open field agriculture would support Overton's traditional argument of the importance of enclosure for the gains in agricultural productivity. However, the whispers of price responsiveness on the manors might suggest that open fields were becoming more efficient, supporting Allen's argument that the first agricultural revolution was carried out by small farmers on open fields.

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Introduction

Medieval economic historians have heatedly debated the cause of the decline in yields on the Winchester manors before the Black Death. For Postan, declining yields were the inspiration for his Neo-Malthusian or population-resources model of medieval economic development. Postan argued that as population increased before the Black Death, greater levels of marginal land were put under cultivation causing a decrease in yields in the century before the Black Death.[2] Titow and later Farmer argued that the decline in yields was caused by chronic undermanuring because of low stocking densities on the Winchester manors.[3] However, no historian to date has produced unambiguous evidence that there was soil fertility decline over the course of the thirteenth century.[4] More recently, Campbell has argued that exogenous climate variation needs to be given more prominence in the study of medieval agriculture, especially in the subsistence crises of the fourteenth century.[5] In addition, Campbell, Stone and Dodds have sought to connect changes in yields in both the seigniorial and peasant agricultural sectors with the rising commercialization of the thirteenth and fourteenth centuries. Campbell has argued that market incentives and pressures shaped technological innovation and intensified production in the manorial sector.[6] Stone has argued that reeves were price responsive in allocating labour and capital on the manor so that yields were higher when grain prices were higher, and lower when grain prices were lower. Thus, variation in crop yields had more to do with reeves' decisions about profit-maximization than with environmental degradation.[7] Dodds has also argued that peasants in northeastern England were price responsive adjusting their total grain output in accordance with price fluctuations.[8] None of these historians, however, have evaluated yield-raising techniques using advanced statistical methods.

Analyzing whether reeves were able to adjust their total output by raising or lowering yields is complicated because yields were affected by many factors that were beyond the reeves' control, the most important of which was weather variation. However, the relative effectiveness of various yield-raising techniques can be tested if one controls for annual weather variation and geographical factors influencing yields such as soil types. Therefore, this paper will critically examine Postan, Titow, Stone, and Campbell's assertions by employing regression analysis to measure the influence of annual weather variation, seed rates, acreages sown with legumes, crop rotations, stocking rates, pastoral types, and mixed-farming types on yields per seed and yields

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[2] Postan, *Medieval Economy*, 63-79.

[3] Titow, *Winchester Yields*, 30-31; Farmer, 'Grain Yields on the Winchester Manors', 564-65; Farmer, 'Grain Yields on Westminster Abbey Manors', 347.

[4] Campbell, *Seigniorial Agriculture*, 16-17; Thornton, 'Determinants', 207-10.

[5] Campbell, 'Nature', 287-93; Campbell, *Seigniorial Agriculture*, 22.

[6] Campbell, *Seigniorial Agriculture*, 284-92, 430-40.

[7] Stone, *Decision-making*, 272-76; Stone, 'Medieval Farm Management', 615-17.

[8] Dodds, *Peasants*, 132-4.

per acre of wheat, barley, and oats on the manors of the Bishop of Winchester from 1349-70.

The results from this study also directly contribute to debates about the efficiency of peasant farmers and the chronology of the agricultural revolution. According to the traditional view of the agricultural revolution, rekindled in recent years by Overton, peasant farmers farming common land were inefficient and lacked the drive to innovate as technology improved in the early modern period. Thus, enclosures, the transfer of common land to private property, and the growth of large farms in the second half of the eighteenth and first half of the nineteenth centuries were most important in increasing agricultural productivity.[9] Allen has challenged this traditional view by arguing that there were in fact two agricultural revolutions. The first agricultural revolution took place through the innovation of small farmers in open fields before the parliamentary enclosures reached full prominence after 1750. The second took place in the first half of the nineteenth century after 1815.[10] Allen's argument relies heavily upon the assertion that small farmers working in open fields were just as open to new technology as large farmers with enclosed land. Therefore, the efficiency of medieval yield raising techniques would serve as a starting point for innovation that occurred later in the early modern period. If the yield-raising techniques were ineffective, then this would support Overton's scepticism about the efficiency of open-field agriculture and question Allen's findings of innovation in the early modern period.

[9] Overton, 'Re-Establishing', 1-3.

[10] Allen, 'Tracking', 209; Allen, *British Industrial Revolution*, 57-79; Mingay, *Parliamentary Enclosure*, 11.

The Data I: Direct Evidence on Farming from Manorial Accounts

Applying the statistical rigour of econometrics to problems in medieval history requires large quantities of data. The data used in this paper is derived from two disparate sources: medieval manorial accounts detailing seigniorial agriculture in southern England have provided detailed information about farming and the rural economy; and climate reconstructions produced to measure global warming have facilitated a detailed study of the influence of annual weather variation on the rural economy.

The direct evidence on manorial farming in the fourteenth century was drawn from manorial accounts enrolled in the Winchester Pipe Roll for a majority of the manors held by the Bishop of Winchester. These accounts contain crop yields, acreages sown with various crops, seed rates, grain prices, piece wages, and labour inputs. The accounts were recorded annually at Michaelmas, September 29, after the harvest, when the reeve would be audited by the lord's steward to ensure that the reeve was managing the manor properly and not committing fraud. The precision in the documents and the strict review process assure that the figures recorded in the accounts were fairly reliable and may be subjected to econometric scrutiny. The data used for this dataset was not collected from the original documents but were extracted from the notes of David Farmer held in the archives at the University of Saskatchewan, from Bruce Campbell's crop yield database, and from Jan Titow's notes in the Hampshire Record Office.[11] The following paragraphs describe the medieval data drawn from the accounts and the limitations of this data as they apply to the current study.

The dataset is a panel dataset of 49 individual manors held by the Bishop of Winchester from 1349 to 1370. The panel is strongly balanced but does have some missing data because the manorial accounts were damaged or have not survived. Although the panel is not perfectly balanced, the survival or damaging of certain documents should not influence the economic functioning of the manors studied here.

The Winchester manors were not wholly representative of all demesnes across England at the time, but they were more representative than has sometimes been suggested.[12] They spanned a great distance from Somerset to Surrey, and Hampshire to Buckinghamshire (Map 1 – maps included in appendix). They included most of the cropping and husbandry types described by Campbell that were present after the Black Death: four of the six cropping types, five of the five pastoral husbandry types, and six of the seven mixed-farming types (Maps 2-4).[13] The average acreage in seed (1362-4) ranged from 43 acres on Bitterne manor in southern Hampshire to 489 acres on East Meon manor also in southern Hampshire with a median across all manors of 134 acres (Map 5).

[11] University of Saskatchewan Archives, The Papers of David Farmer, Series III, Boxes 11, 12, and 14; Campbell, 'Crop Yields', database; Hampshire Record Office, Titow Research Papers, 97M97/B1, 97M97/B5.

[12] Stone, *Decision-Making*, 19-20.

[13] Campbell, *Seigniorial Agriculture*, 275-93.

Many of the manors followed three-course rotations or sowed almost exclusively wheat, barley and oats (Map 6). This pattern was fairly common throughout Southern England with 53.3 per cent of demesnes in Campbell's demesne dataset falling into these production types.[14] However, the Winchester manors along the Thames and in the Chilterns and Cotswolds sowed large amounts of mixed grain and had a ready market for their produce in London, making them similar in some ways to the productive and commercialized manors of East Anglia and Kent (Map 7). The composition of cropping and husbandry types, however, does not follow the national pattern. More intensive cropping and mixed-farming types are underrepresented in the sample and the manors are too large to accurately capture the smaller production strategies on manors held by lay lords. Therefore, it is difficult to extend all findings from the Winchester manors to a broader context of Post-Black Death England. However, when all 49 Winchester manors are studied as a whole, they form the most representative sample of seigniorial production that exists anywhere and provide better conclusions than most studies of the manorial economy, which focus on one or two manors.

Crop yields per seed for wheat, barley and oats were drawn from Bruce Campbell's database of medieval agricultural yields. For Campbell's large multi-century dataset, he measured agricultural yields as yields per seed, the ratio of grain threshed after the harvest to grain planted before the harvest because measurements of land were not standardized throughout the country and because yields per acre could be affected by seeding rates, the amount of seed planted per acre.[15] However, by the Black Death measured acres, which were standardized and more precise, had generally replaced the customary acres of the thirteenth century and seed rates were recorded by Farmer.[16] This made it possible to calculate crop yields per acre for wheat, barley and oats for the period as well. Yields per acre were calculated from Titow's notes for 34 of the 49 manors above and helped ensure that the empirical findings of this study were robust to multiple measures of productivity.[17] Simple Pearson correlations between the two different kinds of yields were very high (wheat 0.91, barley 0.91, oats 0.84), and the results were very similar.

Farmer recorded the acreage of wheat, barley and oats sown on each of the Winchester manors.[18] In order to compare acreages sown across manors in fixed effects, pooled ordinary least squares (POLS), and generalized least squares (GLS) regressions, it was necessary to standardize the acreages: the acreage of each crop sown in a given year was divided by the average acreage of that crop sown on the manor over the entire period. This measure reflects changes in crops sown in a particular year from the average acreage of crops sown on the manor.

[14] Campbell, *Seigniorial Agriculture*, 277.

[15] Campbell, 'Crop Yields', database.

[16] Harvey, *Manorial Records*, 729-30.

[17] Hampshire Record Office, Titow Research Papers.

[18] University of Saskatchewan Archives, The Papers of David Farmer, Series III, Box 10, Folder 1, parts 1-4.

Acreages sown with mixed grains and fodder crops were recorded in Titow's notes annually for the 34 manors mentioned above. The crops were important because mixed grains were among the most commercial crops and nitrogen-fixating, leguminous fodder crops could potentially increase soil fertility and thus yields. In order to account for fodder and mixed grain production, both annual and average acreages planted with fodder crops and mixed grains on each manor were calculated for the period. Map 6 shows the percentage of arable land on each manor dedicated to wheat, barley, and oat production as well as fodder and mixed grain production.

Farmer also recorded the seed rate for wheat, barley, and oats. Seed rates did not vary much on the Winchester manors in this period, but changing seed rates were another way that reeves could adjust their production strategies to environmental and economic conditions. Seed rates were generally higher for spring-sown crops than for wheat; most Winchester manors sowed wheat seed at rates that Campbell deemed low to moderate (2.0-2.5 bushels per acre), while barley and oats were sown at higher levels (over 4.0 bushels per acre). Spring-sown grains may have been sown more thickly to reduce the amount of labour required for weeding.[19]

Livestock information for the Winchester manors came from two sources. Annual sheep stocking rates were collected from the appendixes of Martin Stephenson's dissertation at the University of Cambridge for 36 of the 49 manors.[20] In addition, Farmer recorded annual stocking densities on the various manors from 1362-64, including the number of sheep and the number of cows and horses combined. Therefore, along with Campbell's pastoral and mixed-husbandry types, the number of sheep and the number of cows and horses standardized for each manor based on the total acreage sown were included in the regressions to test how stocking densities influenced yields (Maps 8-9). These stocking densities will provide insight into manure availability and the demand for fodder crops on the different manors.

Farmer also recorded and calculated many local and regional price series for wheat, barley, and oats. Farmer's weighted annual average prices for wheat were available in his notes for each Winchester manor. To obtain the annual weighted average price for each manor, Farmer divided the total revenue gained from sales of a particular grain in a year by the total quantity of that grain sold. Unfortunately, wheat price data was not available for all years, so manor specific prices were interpolated with Farmer's regional price series. The interpolated prices made up less than 10 per cent of the data. Barley and oat prices were either not available on a manor specific level or had too many missing values to be used at the manor level. Therefore, Farmer's regional price series, which were the arithmetic mean of the prices on manors in each region, were used in the regressions. These regional series were interpolated using Farmer's national series.[21] Farmer's national wage series was not

[19] Campbell, *Seigniorial Agriculture*, 309-15.

[20] Stephenson, 'Productivity of Medieval Sheep', 292-4.

[21] Farmer, 'Prices and Wages' (1991), 501-25; Farmer, 'Prices and Wages', (1988), 787-817; University of Saskatchewan Archives, The Papers of David Farmer, Series III: Box 10, Folder 30; Box 12, Folder 50; Box 14, Folders 1, 2, and 5.

available in disaggregated form among the scanned copies of his notes, so the national reaping wage series was used in the regressions.[22]

[22] Farmer, 'Prices and Wages' (1991), 501-25.

The Data II: Production and Soil Types

There were several important aspects of the manorial economy that could not easily be quantified such as the cropping rotations in place, the animal husbandry production system, and the degree of integration between the arable and pastoral sector. Campbell has developed classifications for each of these categories based on cluster analysis performed on a large sample of manors in late medieval England. He defined classifications for before and after the Black Death and found significant overlap between these production types across the Black Death. [23] However, because the period studied in most detail here, 1349-70, was directly after the Black Death, it is possible that many manors were still transitioning from one classification to the next in this period. Each of these classifications provides a more precise way of understanding which factors influenced reeves' ability to adjust their production strategies. There is not space here to define each classification in great detail, but they are summarized in Table 1 with some additional comments below.

Table 1: Description of Campbell's cropping, pastoral husbandry and mixed farming types.

Type Number	Description	Number of Manors
	Cropping Types	
1	Intensive cultivation with legumes	1
3	Cultivation with mixed grains	6
4	Spring-sown crops predominant	19
5	Three-course cropping of wheat and oats	13
	Pastoral Husbandry Types	
1	Non-working cattle and sheep predominant with horses as draught animals	1
3	Non-working cattle and sheep predominant with oxen and horses as draught animals	21
4	Non-working sheep specialization with oxen as draught animals	13
5	Working animals predominant with a swine specialization and oxen as draught animals	2
6	Only working cattle on manor with oxen as draught animals	2
	Mixed Farming Types	
1	Intensive mixed farming	3
2	Light-land intensive	2
3	Mixed farming with sheep	13
5	Sheep corn husbandry	10
6	Extensive mixed farming	7
7	Extensive Arable Husbandry	4

Source: Campbell, *Seigniorial Agriculture* (2000).

Campbell's classifications were only defined for 39 of the 49 Winchester manors in the dataset, so all discussion of the influence of these types is reduced to these

[23] Campbell, *Seigniorial Agriculture*, 103-20, 178, 275-93, 441-52 demesne level classifications.

manors. Concerning Campbell's cropping types, lower numbered cropping types were more intensive and therefore involved planting more fodder crops and mixed grains than the higher numbered types (Map 2).[24] Campbell's pastoral-husbandry types were defined by three key parameters: whether non-working or working animals were predominant on the manor, which animal was most prominent on the manor, and whether oxen or horses were used for draught labour. Manors with more non-working animals tended to have more manure available for spreading, while manors with more working animals had higher fodder requirements (Map 3).[25]

Campbell's mixed-farming types attempt to measure the integration between the pastoral and arable sectors on the manor. Generally the lower numbered mixed-farming types practiced the most intensive production strategies and were most integrated between the pastoral and arable sectors. The higher numbered mixed-farming types practiced extensive production strategies and had relatively little integration between the pastoral and arable sectors (Map 4).[26]

Campbell also generously provided me with soil types for 44 of the 49 Winchester manors in this study (Map 10). Soil types were classified into three types: fine loam soil, sandy loam soil, and heavy clay soil. These different soil types reveal more about the size of particles in the soil and the way that precipitation was drained on the manor than about the general fertility of the soil itself, although loamy soils tended to be more fertile than heavy clay soils. Heavy clay soils drained water slowly and were prone to becoming waterlogged, whereas fine loam and sandy loam soils drained water more quickly. Clearly, this dataset is a good foundation for the robust analysis of yield-raising techniques that will follow.

[24] Campbell, *Seigniorial Agriculture*, 275-91.

[25] Campbell, *Seigniorial Agriculture*, 103-20.

[26] Campbell, *Seigniorial Agriculture*, 176-83.

The Data III: Modelling Medieval English Climate

Bruce Campbell has made the greatest strides to date toward incorporating climate into medieval economic history in his Tawney Lecture and article ‘Nature as Historical Protagonist’.[27] He uses thirty-year moving averages of different series and graph them next to moving averages of prices and yields. He also measures yields as an average measure of aggregate output for the manorial sector, not at each manor individually. He therefore measures the effect of long-term change in climate on long-term change in yields and prices, but there are certainly short-term effects that would not be captured by this method. This paper takes a different approach focusing on the influence of short-term weather variation rather than medium- or long-run trends in climate.

Modelling medieval English climate and weather patterns is not an easy task. There are very few medieval records that provide useful and systematic information about annual weather variation.[28] Therefore, nineteen climate indexes reconstructed from dendrochronology, ice core, and other sources were used to proxy annual weather variation in the fourteenth century: seven Northern Hemisphere temperature reconstructions; four reconstructions of Dutch temperatures from historical sources; one series for temperatures in northern Sweden; a reconstruction of the North Atlantic Oscillation (NAO); a measure of precipitation for northern Scotland from stalagmite width; and five oak-growth reconstructions from England, Northern Ireland, and the Netherlands.[29] With the exception of the NAO series, none of these series were smoothed, so they truly capture annual weather variation in their locations. Because many of these series explain similar weather variation, they were highly correlated and could not be included together in the regression analysis without risking multicolinearity. However, if only a few of the series were input into the regression analysis there was a risk that significant weather variation would have been excluded from the model. Therefore, factor analysis was employed to reduce the data into series that were not correlated and captured a wide range of variation from a number of sources.

Factor analysis is ‘a statistical technique used to identify a relatively small number of factors that explain observed correlations among variables’.[30] These factors are uncorrelated with each other and therefore can be used in regressions without any problems of multicolinearity. The factor analysis was carried out on the nineteen climate reconstructions for the entire fourteenth century. This ensured that the long-run relationships between the variables were drawn out, not short-term anomalies.[31]

After the factors were extracted using principle components analysis and varimax rotation was completed, four sets of factor scores were drawn from the nineteen

[27] Campbell, ‘Nature’, 2010.

[28] The following are the exception to that rule: Le Roy Ladurie, *Times of Feast*, 50-64, 368-75; Chuine *et al.*, ‘Grape Ripening’, 289-90; van Engelen, *et al.*, ‘Millenium’, 101-5.

[29] For sources for weather variables see Table 1 and Electronic Datasets section of bibliography.

[30] Norusis, *SPSS*, 385.

[31] Norusis, 385-421.

original series.[32] Three of the four factor scores represent clear types of data in the rotated component matrix table (Table 2). Factor 1 is strongly correlated with all of the reconstructions of Northern Hemisphere temperatures. Factor 2 is strongly correlated with the oak dendrochronology series for Northern Ireland, England, and the Netherlands. Factor 3 is strongly correlated with both the Dutch summer and winter temperatures. The group of variables correlated with factor 4 did not form a neat category, but factor 4 explained a significant percentage of the variance among the variables and was therefore included in the regressions.

Table 2: Rotated Component Matrix for Weather Factors – Factor 1 corresponds with northern hemisphere temperatures (NHT). Factor 2 corresponds with oak-growth reconstructions. Factor 3 is correlated with Dutch temperatures. Factor 4 does not follow any meaningful pattern.

Climate Reconstructions	Factor 1	Factor 2	Factor 3	Factor 4
NHT: (Mann)	0.778			0.312
NHT: (Moberg)				-0.781
NHT: STD recon (Darrigo)	0.835			
NHT: RCS recon (Darrigo)	0.846			
NHT: (Hegerl)	0.785	0.355		
NHT: (Ammann)	0.806			0.346
NHT: RCS reconstruction (Esper)	0.752			
Netherlands/Belgium Temp (Osborn)			0.973	
Dutch Winter Temperature (Engelen)			0.799	
Dutch Summer Temperature (Engelen)			0.616	
Dutch Year Temperature (Engelen)			0.984	
Tornetrask, N. Sweden (Osborn)				0.570
Winter North Atlantic Oscillation Index (Trouet)		-0.594		0.326
Stalagmite Width Scotland (Proctor)		0.475		-0.373
Oak Growth: Sheffield (Baillie)		0.887		
Oak Growth: London (Baillie)	-0.451	0.370		
Oak Growth: Southern England (Baillie)		0.872		
Oak Growth: Belfast (Baillie)		0.634		
Oak Growth: Netherlands (Baillie)		0.589		

Extraction Method: Principal Component Analysis.
Rotation Method: Varimax with Kaiser Normalization (Rotation converged in 5 iterations).
Values are correlations between each factor and the climate reconstructions. Values under 0.3 we suppressed to ease comprehension of patterns.

Sources: See electronic datasets section in bibliography.

It is fairly clear that factors 1 and 3 represent temperature because the series that they were highly correlated with were specifically designed to measure temperature, but factor 2 was more nebulous. Oak growth is responsive to a number of climate factors and other environmental characteristics. Baillie argues that it is best to think of oak growth as a black box of climate conditions that were either conducive to or unfavourable for oak growth.[33] In general, oaks grow better under cool and rainy conditions, but oak growth series cannot simply be taken as a proxy for

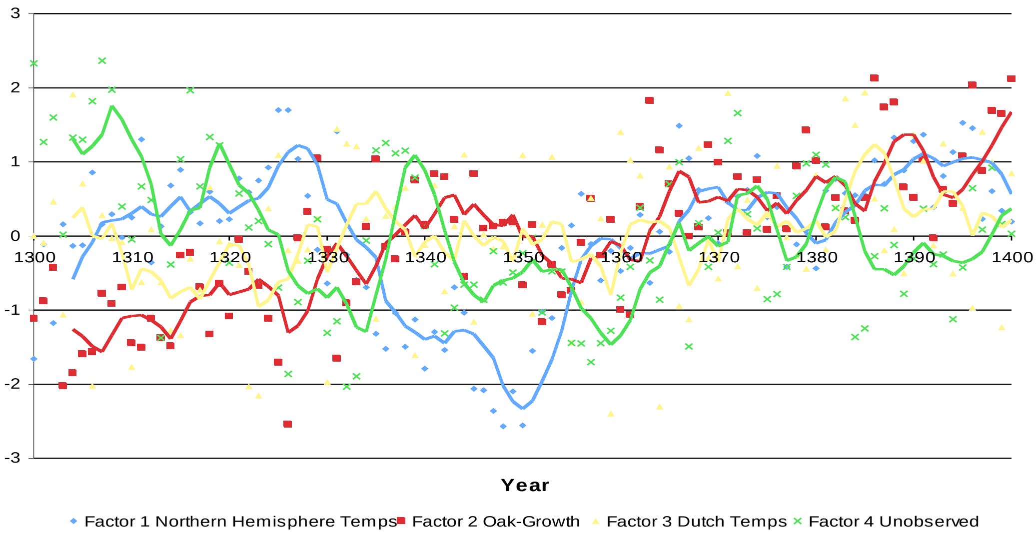
[32] Eight factors had Eigen values above one, but the scree plot showed a clear break in the percentage of variation added by each factor between factor 4 and 5. Thus, the first four factors were retained for rotation and later used in the regressions.

[33] Baillie, *Slice*, 142-3.

precipitation.[34] In order to make dendrochronology data more precise, scientists have begun to look at tree species at the edge of their geographical range, either in elevation or latitude, where the tree's growth is mostly limited by one climate factor.[35] However, the oak-growth series in use here are from oaks in the centre of their geographic range, making it extremely difficult to understand whether they are proxying temperature or precipitation more strongly. Fortunately, several of the oak growth series were highly correlated with Northern Hemisphere temperatures. This correlation is removed by the factor analysis from the dendrochronology series, so although we cannot be certain about what the oak-growth variables were representing, factor 2 will reflect precipitation variation more than temperature variation and can be used cautiously as a measure of precipitation.

The factor scores drawn from the factor analysis were used to represent annual weather variation over the fourteenth century (Figure 1). Because of the low productivity and limited technology of medieval agriculture, annual weather variation could have potentially played a very significant role in determining yields and prices from year to year. These four sets of factor scores will provide a robust estimation of annual, national weather variation with which to test the influence of climate on the medieval economy.

Figure 1: Weather factors with 5-year moving averages, 1300-1400.



Sources: See factor analysis in text and climate series in electronic datasets section of the bibliography.

[34] Campbell, 'Nature', 287-93.

[35] Hughes, 'Dendrochronology', 100.

Evaluating Yield-Raising Strategies

As mentioned above, medieval historians have posited a number of factors that influenced grain yields without testing them in a statistically robust manner. Postan suggested that soil fertility was most important in determining yields. Titow and Farmer highlighted the availability of manure from livestock on the manors. Campbell suggested that long-term weather patterns were the most important factor determining yields. Finally, Stone argued that reeves' allocation of labour inputs in response to economic incentives had the largest influence on yields. This section therefore attempts to test these various hypotheses.

Before exploring the empirical results below, it is first necessary to discuss the data and econometrics used to analyze the wheat, barley, and oat yield regressions. The dataset used in this analysis was the 49 Winchester manor panel described above. Fixed-effects regressions were possible for the wheat yield regressions and for some but not all of the barley and oat yield regressions because there was serial correlation in the idiosyncratic errors. In order to account for the serial correlation, Generalized Least Squares (GLS) models were used for barley and oat yield regressions. Because fixed-effects regressions factor out inter-manor variation, Pooled Ordinary Least Squares (POLS) regressions were used for wheat yields and additional GLS models were used for barley and oat yields to understand how manor specific variables influenced grain yields. These manor-specific variables included the average number of sheep, cows and horses on a manor, cropping patterns, mixed husbandry types, and regional economic effects. Rather than discussing each grain separately, we will explain how environmental factors, planting decisions, livestock husbandry, and economic incentives affected grain yields.

It is also important to highlight some of the weaknesses in the way yield-raising techniques are measured in this paper. This paper targets annual decisions that reeves could make to raise yields, but it is less capable of capturing the influence of complex production systems on yields. Campbell's cropping, pastoral husbandry, and mixed-farming types are evaluated using dummy variables, but this is not an entirely satisfactory method. Likewise, yield-raising techniques are always measured against yields per seed or per acre sown, but there is evidence that some of the most advanced manors had relatively low yields per acre because they were planting a larger portion of the arable with crops and leaving fewer acres fallow than their less intensive counterparts.[36] Therefore, manors with low yields per acre sown could have high levels of total arable output per arable acre.

Unfortunately, total arable land on a manor is difficult to calculate, especially given the nature of the evidence in Titow and Farmer's notes, and was not possible to compute for this paper. More importantly, both of the problems highlighted above deal with differences in production systems, which should only affect the average level of yields on different manors. Although Campbell does find that manors closer to commercial centres practiced more intensive agriculture, reeves could not switch production systems easily, making path dependency and geographical conditions

[36] Campbell, *Seigniorial Agriculture*, 306-9; Thornton, 'Determinants', 188-95.

important barriers to shifting production systems.[37] This paper, therefore, focuses on measuring the yield-raising strategies available to all manors regardless of their production type.

[37] Campbell, *Seigniorial Agriculture*, 284-92.

The Influence of Environmental Factors on Yields

In order to evaluate the yield raising strategies that reeves employed on their manors, it is first necessary to understand and control for environmental influences on yields that were beyond the reeve's control. The two most important environmental factors influencing yields were weather variation and differences in soil types. Different grains were better suited for certain weather and soil conditions, and different soil types drained water more slowly than others and could therefore exacerbate the negative effects of either droughts or heavy rains on yields.

The influence of annual national weather variation on yields was tested using the weather factors described above. These weather factors are an imperfect proxy for the influence of weather on yields because small local events such as hailstorms and flooding could be extremely detrimental to crops and cannot be captured in these proxies. However, it is reassuring that the weather factors were always significant and important in both the yield per seed and yield per acre regressions, although they affected each grain in a different way. The different responses of the grains to varying weather conditions and the strength of weather conditions in determining yields are intrinsically interesting and deserve some discussion here.

Factors one, two, and three were significant in the wheat regressions (Table 3). Factor one, representing northern hemisphere temperatures, and factor three, representing Dutch temperatures, had a significant positive effect on wheat yields. A positive relationship between temperatures and wheat yields is sensible because higher annual temperatures provided reeves with a longer growing season and milder winters, which would give the wheat crop more time to mature throughout the year and allow the wheat to develop more during the winter.[38] There was a strong negative relationship between factor two, oak growth, and wheat yields. This relationship is expected because conditions good for oak growth, cooler temperatures and higher rainfall, are detrimental to wheat production. Responses to factor one and factor two were often stronger and more significant than factor three. Factor four, the unobserved weather effect, was insignificant in the wheat yield regression.

Barley yields per seed and per acre responded in the opposite direction to the weather factors than wheat yields (Table 4). Increases in northern hemisphere temperatures and Dutch temperatures, factors one and three, led to a decrease in the barley yield. It is difficult to explain this relationship because one would expect barley to also benefit from a longer growing year. If the growing year were longer, the spring crop could be planted earlier in the season and would have more time to develop before the harvest. However, it may be the case that the subspecies of barley planted in medieval England thrived in cooler conditions.[39] There was a significant positive relationship between barley yields and oak tree growth, suggesting that barley was well suited to cooler and wetter weather. These results concur with the literature on spring crops, which have generally been found to be more resistant to

[38] Jones, *Seasons*, 43-52; Campbell, 'Nature', 287-301.

[39] These strange results may also be influenced by small levels of winter barley being sown in addition to spring barley. However, Farmer and Titow did not separate winter and spring barley clearly in their notes, making it difficult to account for these differences in the regressions.

poor weather than wheat.[40] Finally, factor four, the unobserved weather effects, had a positive, significant influence on barley yields.

Table 3: Regressions measuring the influence of production decisions, weather, and labour allocation decisions on wheat yields per acre and per seed.

Wheat Yields (dependent)	1	2	3	4
Model	FE	POLS	FE	POLS
Heteroskedasticity	Robust	Robust	Robust	Robust
Serial Correlation	N/A	N/A	N/A	N/A
Coefficients	Unstand.	Unstand.	Unstand.	Unstand.
Yield Type (dependent)	Wheat Acre	Wheat Acre	Wheat Seed	Wheat Seed
N	518	518	697	697
Constant	10.049**	5.735**	5.121**	4.287**
	(3.90)	(2.80)	(5.46)	(6.25)
Outcomes of Production Decisions				
Wheat Seed Rate	-0.006	2.209**	-0.717	0.018
	(-0.01)	(4.57)	(-1.94)	(0.13)
Index Wheat Sown	-3.457**	-3.571**	-0.551	-0.655*
	(-3.05)	(-3.01)	(-1.92)	(-2.12)
Index Barley Sown	0.050	0.287	0.060	0.174
	(0.24)	(0.69)	(0.66)	(1.26)
Index Oats Sown	0.593*	0.950*	0.061	0.172
	(2.28)	(2.28)	(0.40)	(1.18)
Index Mancorn Sown	0.128	0.490*	0.110	0.213*
	(0.73)	(1.99)	(1.66)	(2.22)
Index Dredge Sown	-0.178	0.075	-0.088	0.029
	(-1.48)	(0.45)	(-1.30)	(0.37)
Index Legumes Sown	-0.129	-0.131	0.002	0.025
	(-0.88)	(-0.70)	(0.02)	(0.38)
Outcomes of the Weather				
Factor 1: Northern Hemisphere Temps	0.785**	0.722**	0.388**	0.348**
	(4.95)	(5.00)	(6.34)	(6.61)
Factor 2: Dendochronology	-0.592**	-0.614**	-0.329**	-0.334**
	(-4.62)	(-3.53)	(-7.06)	(-5.39)
Factor 3: Dutch Temperature	0.392**	0.352**	0.096**	0.073
	(3.99)	(2.77)	(2.76)	(1.60)
Factor 4: Unobserved Weather Effects	-0.303	-0.201	-0.016	0.011
	(-1.37)	(-0.79)	(-0.28)	(0.14)
Inferred Responses to Economic Variables				
Reaping Wage (nat)	-0.335**	-0.385**	-0.203**	-0.227**
	(-2.80)	(-2.85)	(-5.14)	(-4.71)
Wheat:Barley Price Ratio (Manor Wheat/Reg Barley)	1.041*	0.584	0.693**	0.390*
	(2.65)	(1.30)	(5.31)	(2.57)
Expected Wheat Price (manor, 5 year, E = 0.7)	0.325**	0.271**	0.157**	0.107**
	(4.71)	(3.58)	(6.20)	(4.15)
R-square	0.22	0.20	0.23	0.16
F-statistic: All Variables	10.03**	11.50**	17.28**	11.88**
F-statistic: Crops Sown	2.54*	3.12**	1.17	2.20*
F-statistic: Economic Variables	10.03**	6.90**	22.70**	13.68**
F-statistic: Weather	20.93**	11.86**	30.47**	17.89**

Coefficients with t-statistics in parentheses: * denotes significance on the 5 % level, ** denotes significance on the 1% level

Sources: see text.

[40] Campbell, 'Nature', 287-301; Campbell, *Seigniorial Agriculture*, 222-26; Jones, 43-52.

Table 4: Regressions measuring the influence of production decisions, weather and labour allocation decisions on barley and oat yields per acre and per seed.

Grain Yield (dependent)	1	2	3	4	5
Model	FGLS	FGLS	FE	POLS	FGLS
Heteroskedasticity	robust	robust	Robust	Robust	robust
Serial Correlation	ps AR(1)	ps AR(1)	N/A	N/A	ps AR(1)
Coefficients	Unstand.	Unstand.	Unstand.	Unstand.	Unstand.
Yield Type (dependent)	Barley Acre	Barley Seed	Oat Acre	Oat Acre	Oat Seed
N	502	654	514	514	713
Constant	-0.586	2.980**	12.172**	11.214**	3.487**
	(-0.19)	(4.22)	(5.21)	(4.41)	(7.93)
Outcomes of Production Decisions					
Seed Rate	3.119**	0.040	0.180	0.375	-0.356**
	(6.46)	(0.38)	(0.31)	(0.91)	(-5.65)
Index Wheat Sown	0.164	0.080	-3.220**	-3.187**	-0.061
	(0.18)	(0.89)	(-3.79)	(-3.98)	(-0.84)
Index Barley Sown	-0.961*	-0.390**	-0.106	-0.066	-0.072
	(-2.09)	(-2.85)	(-0.29)	(-0.22)	(-1.04)
Index Oats Sown	0.890	0.069	-1.440	-1.560**	-0.394**
	(1.54)	(0.96)	(-1.84)	(-4.14)	(-4.64)
Index Mancorn Sown	0.378	0.146*	0.183	0.298	0.003
	(1.95)	(2.48)	(0.64)	(1.46)	(0.07)
Index Dredge Sown	0.280	0.053	0.040	0.071	0.044
	(1.72)	(1.21)	(0.34)	(0.56)	(1.29)
Index Legumes Sown	-0.217	-0.000	-0.176	-0.356*	-0.040
	(-1.15)	(-0.00)	(-1.23)	(-2.14)	(-1.10)
Outcomes of the Weather					
Factor 1: Northern Hemisphere Temps	-0.262	-0.037	0.707**	0.708**	0.156**
	(-1.32)	(-0.84)	(4.94)	(4.21)	(5.13)
Factor 2: Dendochronology	0.500*	0.121**	1.112**	1.104**	0.299**
	(2.49)	(2.65)	(5.37)	(5.73)	(8.98)
Factor 3: Dutch Temperature	-0.454**	-0.122**	0.132	0.106	0.068**
	(-3.24)	(-3.89)	(0.84)	(0.69)	(3.03)
Factor 4: Unobserved Weather Effects	1.436**	0.288**	0.591*	0.669**	0.125**
	(5.52)	(4.87)	(2.46)	(2.64)	(2.96)
Inferred Responses to Economic Variables					
Reaping Wage (nat)	-0.563**	-0.169**	-0.223	-0.225	-0.029
	(-3.43)	(-4.39)	(-1.51)	(-1.47)	(-1.09)
Wheat:Barley Price Ratio (Manor Wheat/Reg Barley)	-0.985*	-0.213			
	(-2.11)	(-1.94)			
Barley:Oat Price Ratio (Reg Barley/Reg Oats)	1.729**	0.367**	0.369	0.464	0.057
	(4.11)	(3.81)	(1.02)	(1.06)	(0.82)
Expected Price (manor, 5 year, E = 0.3)	0.729*	0.237**	0.958**	0.846**	0.335**
	(2.13)	(3.18)	(4.05)	(2.76)	(5.37)
R-square			0.25	0.26	
F-statistic or Wald chi2: All Variables	168.23**	136.98**	10.77**	15.03**	274.01**
F-statistic or Wald chi2: Crops Sown	14.74*	17.49**	3.80**	6.76**	25.98**
F-statistic or Wald chi2: Economic Variables	39.55**	30.86**	7.63**	3.55*	30.24**
F-statistic or Wald chi2: Weather	62.79**	59.11**	13.28**	20.50**	163.19**

Coefficients with t or z-statistics in parentheses: * denotes significance on the 5 % level, ** denotes significance on the 1% level

Sources: see text.

Oat yields per seed and per acre had a slightly different pattern as well (Table 4). All factors had a significant and positive influence on oat yields in the regression. Factor two, oak growth, was the strongest and most significant in the regression followed by factors one and four. Factor three, though significant, explained only a small amount of the variation in yields. This pattern is more typical for a spring crop response. Oat yields increased with a longer growing year, but they also thrived in the wetter, slightly cooler conditions that were optimal for oak growth.

There is some concern that weather variation influenced crops differently based on the prominent soil type on the manor. For instance, heavy clay soils were more likely to become waterlogged and cause flooding. Likewise, in sandy soil that drained water quickly, more precipitation might be needed to maintain a healthy crop. If these differences were significant, there might be problems with including manors with different soil types in the same regressions. In order to test whether the weather influenced grain growing in different soil types differently, we estimated separate regressions of grain yields on the weather factors for manors of each soil type and then employed Chow tests to examine whether the coefficients on the weather variables were significantly different than one another between the soil types. There were no significant (at the one per cent level) differences in the way that the weather influenced yields per seed between the different soil types. However, there were significant differences at the one per cent level between the coefficients on the weather variables between sandy loam and heavy clay soils and between fine loam and heavy clay soils for wheat yields per acre and between sandy loam and heavy clay and fine loam and sandy loam soils for barley yields per acre (Table 5). Because these differences appear only when measuring the influence of the weather on yields per acre, they could be a product of the lower sample sizes available for yields per acre or the importance of seed rates in affecting yields per acre. These differences are also contradictory with the yield per seed results, making it difficult to know how to proceed. In general yields per acre are a less precise measure of agricultural productivity, so the evidence from the yields per seed suggests that there were not significant differences in the effect of the weather on yields between the different soil types.

Table 5: Results of Chow tests (F-statistics) examining whether the coefficients on the weather variables in yield regressions were significantly different on manors with different soil types.

	Soil Type Comparison		
Type A	Sandy Loam	Fine Loam	Fine Loam
Type B	Heavy Clay	Heavy Clay	Sandy Loam
Wheat Yield per Seed	1.76	2.72*	0.49
Wheat Yield per Acre	6.11**	3.32**	0.48
Barley Yield per Seed	1.35	1.11	2.12
Barley Yield per Acre	8.95**	1.11	3.42**
Oat Yield per Seed	0.49	2.96*	2.80*
Oat Yield per Acre	0.18	0.98	1.43

* denotes f-stastic significance on the 5 % level, ** denotes the 1% level

Sources: see text.

Soil types did, however, affect the overall level of wheat and barley yields, measured by inputting dummy variables into the yield regressions to represent the soil type categories (Table 6). For both wheat yields per acre and yields per seed, there was a substantial and significant yield penalty for planting wheat in heavy clay soils.

Fine loam and sandy loam soils did not produce significantly different wheat yields on the Winchester manors. This outcome is not unexpected because heavy clay soils did not drain water as quickly and were therefore particularly prone to being waterlogged, which was especially detrimental to wheat. Soil types influenced barley yields per acre and per seed in a different way. Barley yields were higher on heavy clay and sandy loam soil manors than on fine loam soil manors. It is difficult to explain these differences for barley as a crop. Barley is more resistant to heavy precipitation than wheat, so one would assume that it would fare better in soils that did not drain as well, fine loam and heavy clay. However, barley yields were higher in sandy loam soils as well. Soil types did not significantly influence oat yields per acre or per seed. As the hardiest crop, perhaps oats were less influenced by soil types than other crops. Having evaluated and controlled for the most important environmental influences on yields, it is now possible to test the effectiveness of other yield raising techniques employed by reeves on the Winchester manors.

Table 6: Regression measuring the influence of soil type dummies on wheat, barley and oat yields per acre and per seed.

Grain Yields (dependent)	1	2	3	4	5	6
Model	POLS	POLS	FGLS	FGLS	FGLS	FGLS
Heteroskedasticity	Robust	Robust	robust	robust	robust	robust
Serial Correlation	N/A	N/A	ps AR(1)	ps AR(1)	ps AR(1)	ps AR(1)
Coefficients	Unstand.	Unstand.	Unstand.	Unstand.	Unstand.	Unstand.
Yield Type (dependent)	Wheat Acre	Wheat Seed	Barley Acre	Barley Seed	Oat Acre	Oat Seed
N	573	758	553	672	568	782
Constant	8.004**	4.535**	-4.689	0.519	11.970**	4.104**
	(3.81)	(7.30)	(-1.45)	(0.65)	(4.99)	(9.29)
Soil Types (Campbell)						
Fine Loam Soils	(reference)	(reference)	(reference)	(reference)	(reference)	(reference)
Heavy Clay Soils	-1.073**	-0.407**	1.204**	0.462**	0.070	0.050
	(-3.49)	(-3.54)	(2.93)	(3.91)	(0.17)	(0.63)
Sandy Loam Soils	0.097	-0.157	1.736**	0.212*	-0.028	0.081
	(0.35)	(-1.58)	(3.97)	(2.28)	(-0.10)	(1.47)
Controls						
Seed Rates	X	X	X	X	X	X
Index Grain Sown	X	X	X	X	X	X
Annual Weather Variation	X	X	X	X	X	X
Economic Variables	X	X	X	X	X	X
R-square	0.22	0.18				
F-statistic or Wald chi2: All Variables	17.46**	19.36**	222.53**	158.02**	191.65**	337.36**
F-statistic or Wald chi2: Seed Rate	21.20**	0.26	60.41**	23.73**	1.72	57.77**
F-statistic or Wald chi2: Crops Sown	13.15**	5.37*	7.69**	8.79**	15.06**	26.16**
F-statistic or Wald chi2: Economic Variables	5.72**	12.49**	39.27**	35.33**	25.75**	45.89**
F-statistic or Wald chi2: Weather	15.09**	25.04**	63.72**	70.11**	143.51**	189.64**
F-statistic or Wald chi2: Soil Types	8.54**	6.28**	18.77**	16.60**	0.07	2.18

Coefficients with t or z-statistics in parentheses: * denotes significance on the 5 % level, ** denotes significance on the 1% level

Sources: see text.

Influence of Planting Strategies on Yields

Reeves' planting decisions concerning seed rates, planting legumes,[41] and cropping patterns could also have been important yield raising strategies. Although reeves did not change the seed rate, bushels sown per acre, very often, changes in seed rates annually and differences in seed rates between manors could have significant effects on both yields per acre and per seed. Theoretically, increasing seed rates up to a certain threshold would result in an increase in yields per acre, but beyond this threshold, increasing seed rates would face diminishing returns for yields per acre. For yields per seed, however, it would be doubtful that the yield ratio of harvest to seed would maintain the same level or increase as more seed was applied to the same area of land. Therefore, diminishing returns to increasing seed rates should be more apparent from yields per seed than yields per acre. The influence of seed rates also would also be different depending on the type of regression used to test the relationship. In fixed effects regressions, the differences in levels between manors are removed from the regressions leaving only the effect of changes in seed rates. It would therefore be more likely to highlight the diminishing returns of increased seed rates. When pooled OLS or generalized least squares models were employed, the difference in levels between manors would enter into the regression along with the change. These regressions would tend to capture the potential effect of seed rates on yields across space.

In the fixed effects regressions, increasing wheat seed rates had small negative effects on wheat yields though the effect was not always significant (Table 3). In the pooled OLS regressions for wheat yields, the seed rate was insignificant or negative for wheat yields per seed but had a significant positive effect on yields per acre. These results suggest that there were diminishing returns to increasing wheat seed rates on a particular manor but also that manors with higher average wheat seed rates generally had higher yields.

Because there was serial correlation in the idiosyncratic errors for the barley and oat yields, generalized least squares models had to be used to estimate the barley yield models, and it was not possible to employ fixed effects (Table 4). Therefore, all of the regressions reflect the different seed rate levels between the manors. Increases in barley seed rates increased barley yields per acre, but the effect was not as strong or significant for barley yields per seed. Surprisingly there were no diminishing returns (negative coefficients) to seeding rates for barley yields per seed in the regressions. Perhaps the benefits from choking out weeds by sowing barley thickly overcame the diminishing returns faced by having more plants sharing the same nutrients. For oat seed rates there were clear diminishing returns to planting at higher seed rates for oat yields per seed, but there was no significant relationship between oat seed rates and oat yields per acre. This discussion of seed rates highlights the limitations reeves faced when trying to raise yields. Increasing seed rates was not an unambiguous method for increasing yields.

[41] The leguminous fodder crops sown included peas, pulse, beans, and vetches.

Another surprising outcome of reeves' planting decisions was that grain yields were lower when the reeve increased the land under production for each particular grain (Tables 3-4). Thus, wheat yields were lower when the reeve planted more acres with wheat. There are three possible explanations for this negative relationship. First, it is possible that abrupt changes in acreages sown with particular crops interrupted crop rotations and resulted in land being left fallow less frequently, leading to soil exhaustion and decreased yields. Second, reeves perhaps were not able to maintain the same level of labour inputs per unit land when larger amounts of land were sown, especially in the period following the Black Death when there was an acute shortage of labour. Third, the expansion of acreage sown could have pushed production onto marginal lands, reducing yields. It is not clear whether reeves were aware of this yield penalty from planting larger acreages, but it suggests that even sowing larger acreages was not a steadfast method for increasing output.

One of the most important yield-raising technologies highlighted by historians of the early modern period was the introduction of new crops such as legumes and clover as part of crop rotations, which could help replenish the nitrogen in the soil. However, in a recent paper Allen has questioned the short-term effect of the introduction of legumes into crop rotations. Allen argues that the substitution of legumes for spring-sown grains in the late Middle Ages at first had a negative influence on yields because legumes absorbed most of the mineralized nitrogen in the soil and converted it into organic nitrogen in their roots. Plants cannot absorb organic nitrogen, so the introduction of legumes led to a decrease in the mineralized nitrogen levels in the soil and a decrease in yields. However, because the roots of legumes were left in the ground to decompose, the levels of organic nitrogen in the soil increased over time. Organic nitrogen is converted into mineralized nitrogen at a relatively fixed rate, which meant that over several centuries, legumes significantly raised the levels of mineralized nitrogen in the soil, leading to higher yields.[42]

It is possible to test this hypothesis on the Winchester manors. If we assume that all the manors were operating three-field crop rotations and that legumes were planted with the spring crop in the rotation, then it is possible to predict when a certain crop would be affected by either the increased or decreased nitrogen levels left behind by the legumes.[43] The three-field system consisted of dividing the manor into three large fields and planting one crop in each field per year, one with wheat, one with the spring crop of barley, oats, and legumes, and one left fallow. Considering one field, wheat was generally followed by the spring crop, and then the field was left fallow for a year. Thus, the wheat crop would be affected by the acreage of legumes planted in the field two years before. Barley and oats would be affected by the acreage of legumes planted three years before, when the spring crop was last planted in that field. Therefore it is possible to test whether grain yields were influenced by the lagged acreage planted with legumes.

[42] Allen, 'Nitrogen Hypothesis', 194-7.

[43] Campbell, *Seigniorial Agriculture*, 228-30.

Table 7: Regressions measuring the influence of planting legumes on wheat and barley yields per acre and per seed.

Grain Yields (dependent)	1	2	3	4
Model	FE	FE	FGLS	FGLS
Heteroskedasticity	Robust	Robust	robust	robust
Serial Correlation	N/A	N/A	ps AR(1)	ps AR(1)
Coefficients	Unstand.	Unstand.	Unstand.	Unstand.
Yield Type (dependent)	Wheat Acre	Wheat Seed	Barley Acre	Barley Seed
N	530	733	483	617
Constant	9.396**	4.370**	-5.482	1.367
	(3.43)	(4.70)	(-1.22)	(1.43)
Effectiveness of Legumes				
Lag 2 Years Index Legumes Sown	-0.128	-0.129*		
	(-0.86)	(-2.24)		
Lag 3 Years Index Legumes Sown			-0.469*	-0.067
			(-2.44)	(-1.37)
Controls				
Seed Rates	X	X	X	X
Index Grain Sown (only same grain as yield)	X	X	X	X
Annual Weather Variation	X	X	X	X
Economic Variables	X	X	X	X
R-square	0.19	0.20		
F-statistic or Wald chi2: All Variables	10.97**	19.93**	181.42**	154.86**
F-statistic or Wald chi2: Seed Rate	0.70	6.88*	48.14**	0.03
F-statistic or Wald chi2: Crops Sown	10.36**	3.85	14.83**	22.17**
F-statistic or Wald chi2: Legumes	0.73	5.01*	5.95*	1.88
F-statistic or Wald chi2: Economic Variables	10.08**	22.91**	29.76**	41.38**
F-statistic or Wald chi2: Weather	18.42**	31.43**	25.90**	36.18**

Coefficients with t or z-statistics in parentheses: * denotes significance on the 5 % level, ** denotes significance on the 1% level

Sources: see text.

The results are fairly clear. An increase in legumes planted two years earlier had a small but significant negative effect on wheat yields per seed (Table 7). The relationship was not significant for wheat yields per acre, but the coefficients were always negative. Likewise, an increase in legumes planted three years earlier had a small, significant negative effect on barley yields per acre, and though not significant, the coefficients for barley yields per seed were always negative. These findings are further strengthened because when lagged acreages of legumes for other years are included, they do not significantly influence wheat or barley yields. The oat yield regressions do not provide quite as unambiguous results. The legumes planted in the previous two years had a significant negative influence on both types of oat yields (Table 8). The third year lag also had a negative coefficient, but it was not significant. This pattern is difficult to explain. Perhaps because oats and legumes were somewhat substitutable as fodder crops, the amount of fodder crops available from the previous year directly affected oat requirements in the current year, removing incentives to allocate labour to the oat crop.

Table 8: Regressions measuring the influence of planting legumes on oat yields per acre and per seed.

Grain Yields (dependent)	1	2	3	4	5	6
Model	FGLS	FGLS	FGLS	FGLS	FGLS	FGLS
Heteroskedasticity	robust	robust	robust	robust	robust	robust
Serial Correlation	ps AR(1)	ps AR(1)	ps AR(1)	ps AR(1)	ps AR(1)	ps AR(1)
Coefficients	Unstand.	Unstand.	Unstand.	Unstand.	Unstand.	Unstand.
Yield Type (dependent)	Oat Acre	Oat Acre	Oat Acre	Oat Seed	Oat Seed	Oat Seed
N	556	525	494	790	745	703
Constant	5.274*	4.644*	3.892	2.663**	2.908**	2.793**
	(2.45)	(1.99)	(1.31)	(5.82)	(6.17)	(4.91)
Effectiveness of Legumes						
Lag Index Legumes Sown	-0.593**			-0.117**		
	(-3.54)			(-3.45)		
Lag 2 Years Index Legumes Sown		-0.410*			-0.096**	
		(-2.33)			(-2.74)	
Lag 3 Years Index Legumes Sown			-0.192			-0.038
			(-1.05)			(-1.04)
Controls						
Seed Rates	X	X	X	X	X	X
Index Oats Sown	X	X	X	X	X	X
Annual Weather Variation	X	X	X	X	X	X
Economic Variables	X	X	X	X	X	X
R-square						
F-statistic or Wald chi2: All Variables	197.97**	139.68**	132.67**	295.91**	221.26**	257.15**
F-statistic or Wald chi2: Seed Rate	0.05	0.02	0.04	42.79**	48.09**	73.84**
F-statistic or Wald chi2: Crops Sown	11.64**	16.88**	9.85**	17.43**	22.30**	21.51**
F-statistic or Wald chi2: Legumes	12.55**	5.42*	1.11	11.91**	7.53**	1.09
F-statistic or Wald chi2: Economic Variables	23.88**	15.43**	12.41**	42.05**	19.47**	21.84**
F-statistic or Wald chi2: Weather	126.92**	92.69**	99.55**	149.46**	104.64**	107.81**

Coefficients with z-statistics in parentheses: * denotes significance on the 5 % level, ** denotes significance on the 1% level

Sources: see text.

In any case, this evidence directly supports Allen's 'Nitrogen Hypothesis' that there were short-run productivity losses with the introduction of legumes into crop rotations in the late medieval period. These short-run productivity losses were exasperated by the fact that generally only 10-20 per cent of the spring field was sown with legumes, preventing nitrogen build-up after the initial loss of mineralized nitrogen. Planting legumes were clearly not a method of raising yields in the short run and must have been introduced for other purposes, perhaps to provide fodder for livestock.

It is also possible that general cropping strategies provided some efficiencies as a system that could not be captured by the annual yield-raising strategies tested above. For wheat and barley, yields per acre and per seed were generally higher on manors employing more intensive cropping strategies (Table 9). The coefficients were not always significant, but the pattern generally held. Thus, there were added efficiencies from employing the more intensive cropping types, especially types one and three (see Table 1), when compared to the three-course rotation represented by type 5. The exact opposite was true of oat yields. Manors employing more intensive cropping strategies had lower oat yields than type five manors. These more intensive manors were more market oriented, specializing in barley or other brewing grains, and would only have needed to sow enough oats to cover fodder requirements.[44] Therefore, oats

[44] Campbell, *Seigniorial Agriculture*, 286-9.

were less valuable and oat yields were lower on intensive manors than on more extensive manors, which sowed large acreages of oats. These differences in yields across intensive and extensive cropping types highlight the importance of complex production systems in determining yields. However, these production systems could not be changed quickly or frequently because they were often dependent on geographical and economic factors such as soil fertility and proximity to major markets.

Table 9: Regressions measuring the influence of Campbell's cropping and pastoral husbandry types represented as dummies on wheat, barley and oat yields per acre and per seed.

Grain Yields (dependent)	1	2	3	4	5	6
Model	POLS	POLS	FGLS	FGLS	FGLS	FGLS
Heteroskedasticity	Robust	Robust	robust	robust	robust	robust
Serial Correlation	N/A	N/A	ps AR(1)	ps AR(1)	ps AR(1)	ps AR(1)
Coefficients	Unstand.	Unstand.	Unstand.	Unstand.	Unstand.	Unstand.
Yield Type (dependent)	Wheat Acre	Wheat Seed	Barley Acre	Barley Seed	Oat Acre	Oat Seed
N	518	673	498	619	514	686
Constant	4.807*	4.141**	-5.524	2.504**	8.934**	3.281**
	(2.15)	(6.05)	(-1.60)	(3.35)	(3.74)	(6.36)
Cropping Types (Campbell)						
Cropping Type 1	1.981**	0.310	5.544**	1.010**	-1.460**	-0.338**
Intensive cultivation with legumes	(2.81)	(1.28)	(6.26)	(4.80)	(-3.45)	(-4.16)
Cropping Type 3	1.096	0.205	7.434**	0.813**	-0.144	-0.129
Cultivation with mixed grains	(1.91)	(1.05)	(5.31)	(3.56)	(-0.21)	(-1.26)
Cropping Type 4	1.020**	-0.070	2.785**	0.126	0.452	0.044
Spring-sown crops predominant	(3.19)	(-0.63)	(5.42)	(1.08)	(1.40)	(0.68)
Cropping Type 5 Three-course cropping of wheat and oats	(reference)	(reference)	(reference)	(reference)	(reference)	(reference)
Pastoral Types (Campbell)						
Pastoral Type 1	3.093**	1.295**	4.832**	1.087**	1.830*	0.587**
Non-working; Cattle and sheep; Horses draft	(5.20)	(5.97)	(2.97)	(2.59)	(1.98)	(3.04)
Pastoral Type 3 Non-working; Cattle and sheep; Horse and ox draft	(reference)	(reference)	(reference)	(reference)	(reference)	(reference)
Pastoral Type 4	1.968**	0.534**	2.592**	-0.046	-0.429	-0.112
Non-working; Sheep specialization; Oxen draft	(6.27)	(4.94)	(4.95)	(-0.44)	(-1.31)	(-1.79)
Pastoral Type 5 Working; Swine specialization; Oxen draft	(ommitted)	0.213 (1.01)	(ommitted)	(ommitted)	(ommitted)	0.236 (1.38)
Pastoral Type 6 Working; Cattle only; Oxen Draft	(ommitted)	0.019 (0.10)	(ommitted)	-0.594 (-1.64)	(ommitted)	0.451 (1.18)
Controls						
Seed Rates	X	X	X	X	X	X
Index Grain Sown (only same grain as yield)	X	X	X	X	X	X
Annual Weather Variation	X	X	X	X	X	X
Economic Variables	X	X	X	X	X	X
R-square	0.27	0.22				
F-statistic or Wald chi2: All Variables	19.11**	16.53**	230.56**	167.60**	221.65**	318.66**
F-statistic or Wald chi2: Seed Rate	15.41**	0.25	44.29**	0.00	0.00	9.01**
F-statistic or Wald chi2: Crops Sown	5.95*	3.83	8.38**	9.24**	15.74**	17.99**
F-statistic or Wald chi2: Economic Variables	8.95**	13.57**	31.49**	45.64**	20.43**	33.56**
F-statistic or Wald chi2: Weather	15.14**	21.51**	47.53**	46.26**	132.72**	155.47**
F-statistic or Wald chi2: Pastoral Dummies	28.76**	13.16**	32.09**	9.77*	6.05*	18.33**
F-statistic or Wald chi2: Cropping Dummies	4.43**	1.53	58.07**	34.73**	31.09**	35.01**

Coefficients with t or z-statistics in parentheses: * denotes significance on the 5 % level, ** denotes significance on the 1% level

Sources: see text.

Clearly, many of the annual yield-raising production strategies that medieval historians have emphasized in the past were not as efficient as previously thought. Increasing seed rates did not unambiguously raise yields. Increasing the land under production with a certain crop led to diminishing returns to yields. And planting nitrogen-fixating legumes did not increase yields in the short-run. There were some benefits to wheat and barley yields from practicing more intensive forms of crop rotations, highlighting efficiency gains from complex production strategies. However, overall these findings question the ease with which reeves could adjust their output without totally transforming their crop systems.

Influence of the Pastoral Sector and Arable and Pastoral Integration on Yields

Reeves' decisions about livestock production and management could also influence yields because larger flocks and herds increased the availability of manure that could be used as fertilizer and because manors with larger herds of cows and horses had to provide fodder for the animals. In addition, the efficiency of production could have been affected by different combinations of working and non-working animals and by the predominance of horses or oxen as a source of draught power. This section will test the influence of stocking rates (livestock per acre), Campbell's pastoral husbandry types, and Campbell's mixed-farming types on yields.

Table 10: Regressions measuring the influence of stocking rates on wheat, barley and oat yields per acre and per seed.

Grain Yields (dependent)	1	2	3	4	5	6
Model	POLS	POLS	FGLS	FGLS	FGLS	FGLS
Heteroskedasticity	Robust	Robust	robust	robust	robust	robust
Serial Correlation	N/A	N/A	ps AR(1)	ps AR(1)	ps AR(1)	ps AR(1)
Coefficients	Unstand.	Unstand.	Unstand.	Unstand.	Unstand.	Unstand.
Yield Type (dependent)	Wheat Acre	Wheat Seed	Barley Acre	Barley Seed	Oat Acre	Oat Seed
N	594	624	578	609	593	636
Constant	8.103**	5.978**	-2.076	1.566	9.554**	4.199**
	(3.95)	(7.63)	(-0.65)	(1.87)	(4.33)	(7.79)
Livestock						
Annual Number of Sheep per Acre	0.024	0.001	0.046	0.011	0.007	0.017
	(0.14)	(0.01)	(0.26)	(0.29)	(0.07)	(0.68)
Average Sheep per Acre (1349-70)	-0.093	-0.039	-0.160	-0.054	0.062	-0.036
	(-0.51)	(-0.67)	(-0.84)	(-1.24)	(0.52)	(-1.31)
Cows and Horses per Acre (1362-64)	-0.646	-0.292*	0.231	0.028	1.564**	0.346**
	(-1.64)	(-2.04)	(0.43)	(0.19)	(4.66)	(4.59)
Controls						
Seed Rates	X	X	X	X	X	X
Index Grain Sown (only same grain as yield)	X	X	X	X	X	X
Annual Weather Variation	X	X	X	X	X	X
Economic Variables	X	X	X	X	X	X
R-square	0.20	0.16				
F-statistic or Wald chi2: All Variables	14.67**	12.89**	200.02**	131.80**	246.38**	307.84**
F-statistic or Wald chi2: Seed Rate			63.48**	13.99**	5.25*	51.00**
F-statistic or Wald chi2: Crops Sown	14.40**	10.85**	6.45*	6.83**	14.60**	23.45**
F-statistic or Wald chi2: Economic Variables	8.36**	14.60**	49.69**	45.92**	31.62**	38.08**
F-statistic or Wald chi2: Livestock	2.06	2.31	2.49	5.24	24.10**	24.89**
F-statistic or Wald chi2: Weather	9.07**	11.67**	48.16**	45.60**	168.10**	162.92**

Coefficients with t or z-statistics in parentheses: * denotes significance on the 5 % level, ** denotes significance on the 1% level

Sources: see text.

The average number of cows and horses per arable acre (1364-64) on a manor had a significant negative effect on wheat yields, no effect on barley yields, and a significant positive effect on oat yields (Table 10). Higher oat yields on manors with relatively larger herds to feed is sensible; reeves responsible for larger herds would put extra labour inputs into the oat crop to ensure that there was enough fodder to maintain the herd. However, the relatively small negative impact of the number of cows and horses per acre on wheat yields is more difficult to explain. One important point to note is that the potential availability of manure measured by the stocking density was not equivalent to the amount of manure that ended up being used as fertilizer. In the high wage era following the Black Death, it is likely that manuring was carried out less frequently. In fact, evidence from Hinderclay manor in Suffolk has shown that manuring may have declined substantially before the Black Death.[45] Alternatively, Allen has argued that manuring was not as effective at raising mineralized nitrogen levels in the soil as has been previously thought because animals did not bring new sources of nitrogen to the manor; they recycled nitrogen present in the fodder they ate. Allen simulates a model where animals ate 100 per cent of the spring-sown grain on the manor rather than the 15 per cent estimated by Campbell for the fourteenth century, and this raised yields only marginally. Thus, increasing manuring could not lead to large increases in productivity in the long run.[46]

The average number of sheep per acre on a manor did not significantly influence wheat or barley yields, but higher average numbers of sheep per acre had a very small negative effect on oat yields per seed (Table 10). Therefore, the availability of sheep manure did not influence grain yields. In addition, annual sheep stocking densities were never significant in the yield regressions, raising two important issues. First, changes in the annual availability of sheep manure did not influence grain yields. This was also tested using lagged sheep stocking rates to allow for the benefits of folding the sheep on the fallow. None of the lags were ever significant going back four years. Second, the insignificance of annual sheep stocking rates suggests that the arable and pastoral sectors were somewhat segregated. At least in the twenty years studied here, pastoral sheep farming did not take labour away from the arable to the extent that yields suffered as the reeves attempted to manage growing flocks over the period.

As mentioned above with regard to cropping types, it is also important to test whether different production systems were more or less efficient. Campbell's pastoral-husbandry types had a small but significant influence on wheat, barley, and oat yields (Table 9). Manors employing pastoral type one with non-working cattle and sheep predominant and horses used as draught labour had higher yields for all the grains, which might suggest some benefits to yields from the greater availability of manure and from having efficient horses ploughing rather than oxen. Wheat yields and barley yields per acre were also higher on pastoral type four manors with non-working animals predominant, large flocks of sheep, and oxen used for draught labour. The differences between pastoral types three, five, and six were never significant.

These findings in many ways are contradictory and do not provide a clear effect of the pastoral sector on grain yields. Both pastoral types that had higher yields relative to type three raised predominantly non-working animals but so did type three. Even the effect of using horses as draught labour is unclear because pastoral type one manors used only horses for draught labour and pastoral type four manors used only oxen for draught labour, yet they both had higher yields than type three manors, which employed both horses and oxen for draught labour. The potential availability of manure, the percentage of non-working animals on the manor, and the type of animal, horse or oxen, carrying out draught labour seemed to have had little systematic

[45] Stone, *Decision-making*, 238-9.

[46] Allen, 'Nitrogen Hypothesis', 192-3.

influence on yields. The only typical response to livestock on manors was a tendency for reeves to allocate extra labour to the oat crop on manors with larger herds.

Table 11: Regressions showing the influence of Campbell's mixed farming types represented as dummies on wheat, barley and oat yields per acre and per seed.

Grain Yields (dependent)	1	2	3	4	5	6
Model	POLS	POLS	FGLS	FGLS	FGLS	FGLS
Heteroskedasticity	Robust	Robust	robust	robust	robust	robust
Serial Correlation	N/A	N/A	ps AR(1)	ps AR(1)	ps AR(1)	ps AR(1)
Coefficients	Unstand.	Unstand.	Unstand.	Unstand.	Unstand.	Unstand.
Yield Type (dependent)	Wheat Acre	Wheat Seed	Barley Acre	Barley Seed	Oat Acre	Oat Seed
N	518	673	498	619	514	686
Constant	9.460**	5.864**	-2.840	2.544**	10.809**	3.282**
	(4.18)	(8.49)	(-0.83)	(3.32)	(4.31)	(5.92)
Husbandry and Cropping Types (Campbell)						
Mixed Farming Type 1	1.598**	0.356	5.639**	0.783**	2.246**	0.238
Intensive mixed farming	(2.98)	(1.82)	(3.62)	(2.65)	(2.90)	(1.61)
Mixed Farming Type 2	(ommitted)	0.999**	(ommitted)	0.402	(ommitted)	0.013
Light-land intensive		(4.02)		(1.57)		(0.08)
Mixed Farming Type 3	0.123	0.040	1.958**	0.558**	0.038	0.030
Mixed farming with sheep	(0.40)	(0.33)	(4.23)	(5.29)	(0.13)	(0.48)
Mixed Farming Type 5 Sheep corn husbandry	(reference)	(reference)	(reference)	(reference)	(reference)	(reference)
Mixed Farming Type 6	-1.798**	-0.751**	-1.124*	-0.229	-0.115	-0.007
Extensive mixed farming	(-5.46)	(-5.77)	(-2.02)	(-1.91)	(-0.30)	(-0.08)
Mixed Farming Type 7	(ommitted)	-0.495**	(ommitted)	-0.346	(ommitted)	0.259
Extensive arable husbandry		(-3.16)		(-1.17)		(1.75)
Controls						
Seed Rates	X	X	X	X	X	X
Index Grain Sown (only same grain as yield)	X	X	X	X	X	X
Annual Weather Variation	X	X	X	X	X	X
Economic Variables	X	X	X	X	X	X
R-square	0.24	0.22				
F-statistic or Wald chi2: All Variables	19.12**	17.45**	189.15**	167.48**	176.49**	246.51**
F-statistic or Wald chi2: Seed Rate	1.33	10.40**	27.37**	0.33	1.27	11.87**
F-statistic or Wald chi2: Crops Sown	7.39**	4.30*	1.49	5.52*	17.96**	19.77**
F-statistic or Wald chi2: Economic Variables	10.47**	14.13**	33.17**	49.35**	19.40**	31.12**
F-statistic or Wald chi2: Weather	14.54**	21.77**	47.08**	45.99**	124.07**	146.85**
F-statistic or Wald chi2: Mixed Husbandry Dummies	14.27**	11.62**	44.18**	55.76**	8.96*	6.15

Coefficients with t or z-statistics in parentheses: * denotes significance on the 5 % level, ** denotes significance on the 1% level

Sources: see text.

However, as Campbell argues, the number of livestock on a manor was unimportant if livestock and arable production were not integrated.[47] Campbell's mixed-farming types, therefore, integrate pastoral-husbandry and cropping types. These mixed-farming types are explained in more detail in Table 1, but generally they vary between different levels of intensive or extensive farming and between varying levels of integration between the arable and pastoral sectors. Manors with more integrated arable and pastoral sectors and intensive farming techniques had higher grain yields, though the differences were not always significant (Table 11). Thus the relative intensiveness with which the arable and pastoral sectors on a manor were integrated could significantly influence yields. However, as mentioned above with regard to cropping types, reeves were not completely free to choose and change the mixed farming type employed on the manor because geographical determinants such as soil fertility and the presence of good pasture played a large role in shaping arable

[47] Campbell, *Seigniorial Agriculture*, 176.

and pastoral production. While intensive, integrated production systems could explain inter-manor variation in yields, reeves could not easily shift production systems.

Three conclusions arise from this discussion of pastoral influences on grain yields. First, the availability of manure did not strongly influence yields as Titow argued in explaining the decline in yields before the Black Death. This raises two possibilities for the manuring thesis of agricultural productivity: either Allen is right that manure did not really add significant amounts of nitrogen to the soil or reeves never expended the labour to spread all of the manure that was available to them. Second, more intensive and integrated methods of production had higher grain yields. Third, fodder requirements played a strong role in determining the demand for oats and other fodder crops, and therefore manors with greater stocking densities of cattle and horses had higher oat yields.

Influence of Economic Factors on Reeves' Decision-making and Yields

So far this paper has struck down many of the yield raising techniques that medieval historians have accepted for years: increasing seed rates and acreage planted with a certain crop did not unambiguously raise yields; adding legumes to crop rotations had a negative effect on all grain yields; and the availability of manure did not influence yields. There is however evidence from this dataset that highlights the best tools that reeves had for increasing their yields. Reeves clearly responded to economic conditions when deploying labour inputs, such as weeding, manuring, harvesting and gleaning, on their manors as Stone has suggested. They responded to short-term fluctuations in labour input costs, opportunity costs between the different grains in production, and expected grain prices.[48] Although the effect of these labour inputs can only be inferred by the influence of economic variables on yields, controlling and targeting labour inputs toward certain crops was the reeve's best tactic in trying to increase yields.

The labour input cost, measured by the national reaping wage, negatively influenced wheat and barley yields as would be expected (Tables 3-4). Reeves considered marginal gains in output from increased labour inputs in a rational way, weighing higher yields from increased labour inputs with the cost of these labour inputs. This effect was strongest and most significant for wheat and barley yields, which were relatively more labour intensive than oats.[49] Labour input costs were not significant for oat yields because oats were the least valuable grain. As long as fodder requirements were being met, increasing labour inputs into the oat crop was not a generally profitable endeavour.

The opportunity costs between the different grains were sometimes also significant to reeves labour allocation decisions. The opportunity cost in allocating labour to the wheat rather than the barley crop, the wheat to barley price ratio, significantly influenced wheat yields. When the wheat price was high relative to barley, reeves allocated more of their labour inputs toward the wheat crop, and wheat yields were higher as a result. The opportunity cost between wheat and barley was also significant to reeves' labour allocation decisions for barley with reeves allocating less labour to the barley crop when wheat prices were high relative to barley prices. This relationship, however, was less significant and important than the opportunity cost between barley and oats; higher barley prices relative to oat prices resulted in more labour being allocated to the barley crop and higher barley yields. Barley decisions may have been influenced more by the opportunity cost between barley and oats because the most labour intensive periods for barley and oats, ploughing, planting, and harvesting, took place at similar times of the year while wheat required intensive labour at different points during the year. Reeves' decisions in allocating labour to oat

[48] Expected prices were calculated using Nerlove's adaptive expectations model, which essentially holds that the expected price is a weighted average of past prices with prices closest to the present being weighted more highly than those farther in the past. Nerlove, *Dynamics of Supply*, 52-55; Askari and Cummings, 'Estimating', 257-8.

[49] Campbell, *Seigniorial Agriculture*, 218.

crops did not significantly respond to the opportunity cost between barley and oats. Reeves also responded to changes in their expected price for each grain in rational ways. When expected prices of each grain were higher, reeves allocated more labour inputs to these crops and the yields were higher.

Clearly, reeves on the Winchester manors were price responsive in their labour allocation decisions, weeding, manuring, harvesting, and gleaning more intensively when the price of wheat and barley were high and labour input costs were low. Although these labour allocation decisions played a smaller role than annual weather variation in determining yields, they were still the most important tool that the reeve had to influence yields year to year. This suggests that medievalists should focus more on how labour is allocated on the manor than on traditional yield-raising techniques such as stocking rates and planting legumes.

In addition, however optimistic this evidence may be for the commercialization model of medieval economic development, we must be cautious in attempting to argue that the output of the agricultural sector was price responsive. First, annual weather variation explained more of the variation in grain yields than other explanatory factors (Table 12). Table 12 presents coefficients of determination from the regression of actual yields on yields predicted by the various sets of factors. Annual weather variation always explained more variation in yields than economic variables, though economic factors were clearly more influential in explaining wheat yields. Livestock variables were also negligible next to the weather. Sometimes production variables (seed rates and acreages sown with various crops) approached or

Table 12: Coefficients of determination from regressions of actual yields on yields predicted by the different factors separately. Thus, annual weather variation (factors 1-4) explains 8.93 per cent of the variation in wheat yields per seed.

		Explanatory Factors			
		Weather	Production	Livestock	Economic
Grain Yield Types	Wheat Yield per Seed	8.93%	0.84%	0.81%	6.72%
	Wheat Yield per Acre	7.31%	6.60%	0.07%	4.20%
	Barley Yield per Seed	6.57%	1.96%	2.00%	3.14%
	Barley Yield per Acre	4.20%	28.29%	1.98%	1.88%
	Oat Yield per Seed	14.22%	7.52%	3.85%	3.15%
	Oat Yield per Acre	16.21%	8.16%	2.49%	1.81%

Sources: see text.

exceeded the variation explained by the weather but this only took place with yields per acre, which were highly influenced by seed rates. This evidence suggests that reeves could only adjust their output within the framework that the weather imposed upon them, and in the end, the weather determined the final outcome. This is especially true considering that the annual weather proxies used in this paper only capture a fraction of the important weather variation that influenced yields. Therefore, it is doubtful that aggregate output of the agricultural sector was price responsive in the fourteenth century.

In addition, reeves were the least risk averse producers in the medieval economy because none of the produce they farmed provided for their subsistence. They could take risks and chase profits without regard for providing their family a minimum of subsistence. These results from manorial sources, therefore, probably represent the upper limit of price responsiveness in medieval agriculture. Finally, total agricultural output was a product of two decisions: how many acres to plant with each grain and how to allocate labour among the crops once the fields had been planted. We have seen evidence that reeves were price responsive in the second decision, but elsewhere I have argued that they were not price responsive in the first.[50]

[50] Schneider, 'Weather', 62-73.

Conclusion

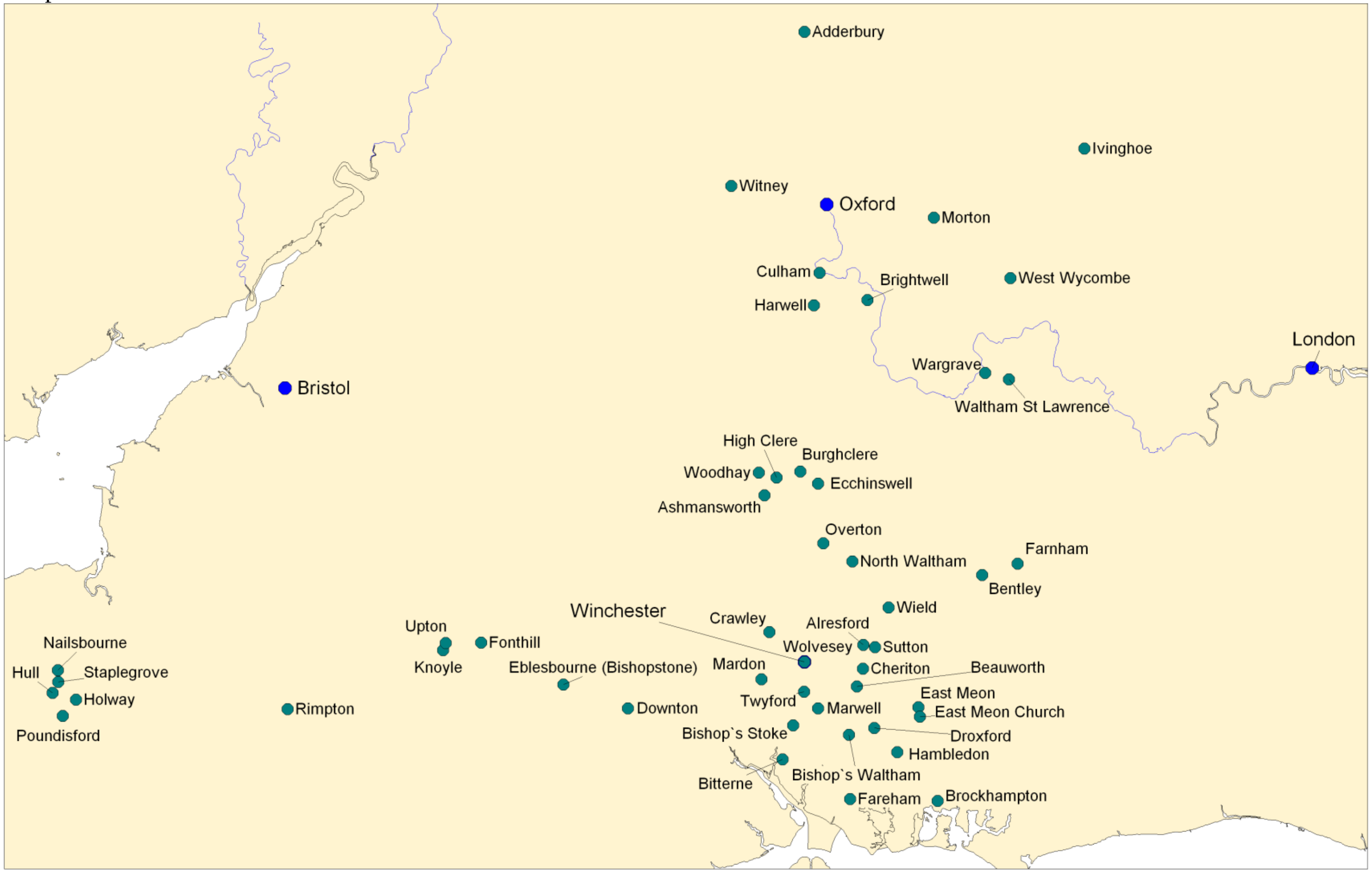
In summary, this paper has made three interesting contributions to the medieval agricultural literature. First, medieval annual weather variation was modelled using temperature, dendrochronology, and precipitation time series from climate scientists and was shown to accurately predict variation in medieval grain yields. Second, many of the yield raising strategies that featured prominently in medieval economic history were shown to be less effective than historians have traditionally thought. Planting greater acreages with nitrogen fixating legumes led to decreased grain yields, and the availability of manure on a manor measured by the stocking rates of sheep, cows and horses had no influence on grain yields. Finally, after controlling for the influence of weather, production decisions, and livestock production on the Winchester manors, reeves clearly allocated labour on their manors based on economic variables such as labour input costs, opportunity costs between different grains and expected prices for each grain. In fact, these labour allocations were the most effective tools that reeves had to control their annual agricultural output. Weather variation, however, did play a very strong role in determining crop yields with the highest joint significance of any dynamic variables in the regressions.

These results challenge Postan's explanation of declining yields before the Black Death. Clearly, there were many factors influencing grain yields that had nothing to do with the decline in soil fertility as production expanded onto more marginal lands. Likewise, differences in stocking rates and thus the availability of manure did not explain variation in yields as Titow and Farmer argued. There is evidence to support both Campbell and Stone's arguments. Weather variation played the strongest role in determining yields from year to year. At the same time, there is concrete, statistically robust evidence that reeves were price responsive in allocating labour to the different crops on the manor as Stone suggested. In fact, the economically driven changes in the allocation of labour had the biggest influence on grain yields other than the weather. This highlights how important ploughing, weeding, gleaning, and potentially manuring could be on the manor. There is also evidence, as Campbell has argued, that more intensive production systems generated higher yields, but these systems were fairly rigid and could not readily be adopted on all manors.

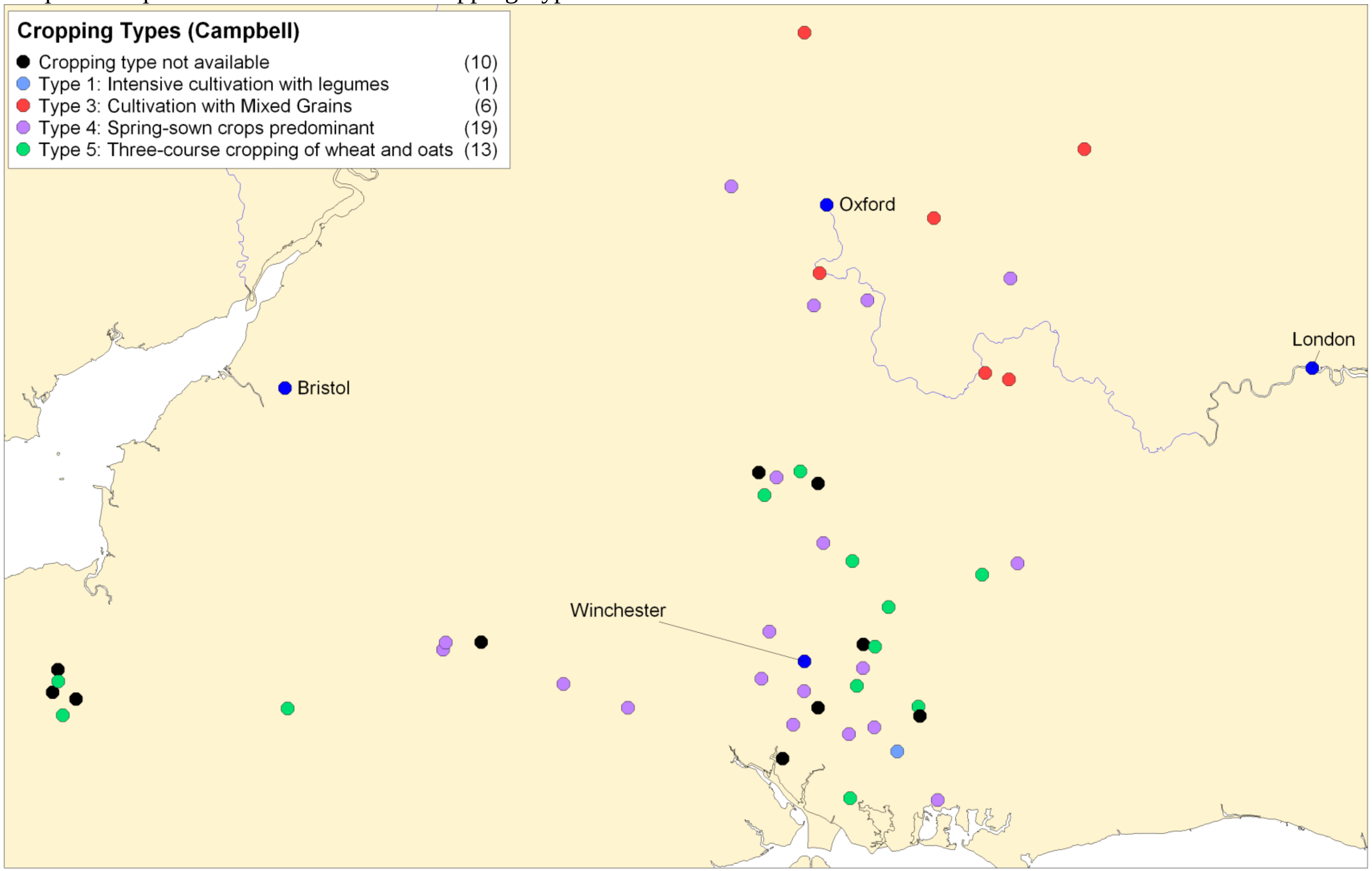
In relation to the timing and drivers behind the agricultural revolution, this paper presents mixed results. On the one hand, medieval yield raising techniques were largely ineffective, and it is unlikely that total output from these manors was affected by prices. This would support Overton's traditional view that open field agriculture lacked the technology and innovative spirit to create an agricultural revolution. On the other hand, reeves appear to have responded to economic conditions within the parameters they could control. They could not change acreages planted to reflect expected prices because of the strict crop rotations required to maintain soil fertility, but after planting decisions had been made, reeves responded enthusiastically to economic factors in allocating labour around their manors. Likewise, efficient, intensive agriculture was practiced on some manors with yield benefits even if these production strategies could not be practiced universally. These two factors may have been the precursors to the innovation of the early modern period that Allen describes.

In addition, the medieval evidence supports Allen's nitrogen hypothesis because planting legumes had short-term negative effects on yields and greater availability of manure did not increase yields. Thus, the eventual long-term benefits from planting legumes and other nitrogen fixators would have made increases in agricultural productivity a long, drawn out affair, occurring over centuries, rather than the sharp increase in the late eighteenth century as Overton has argued.

Map 1: The Winchester Manors

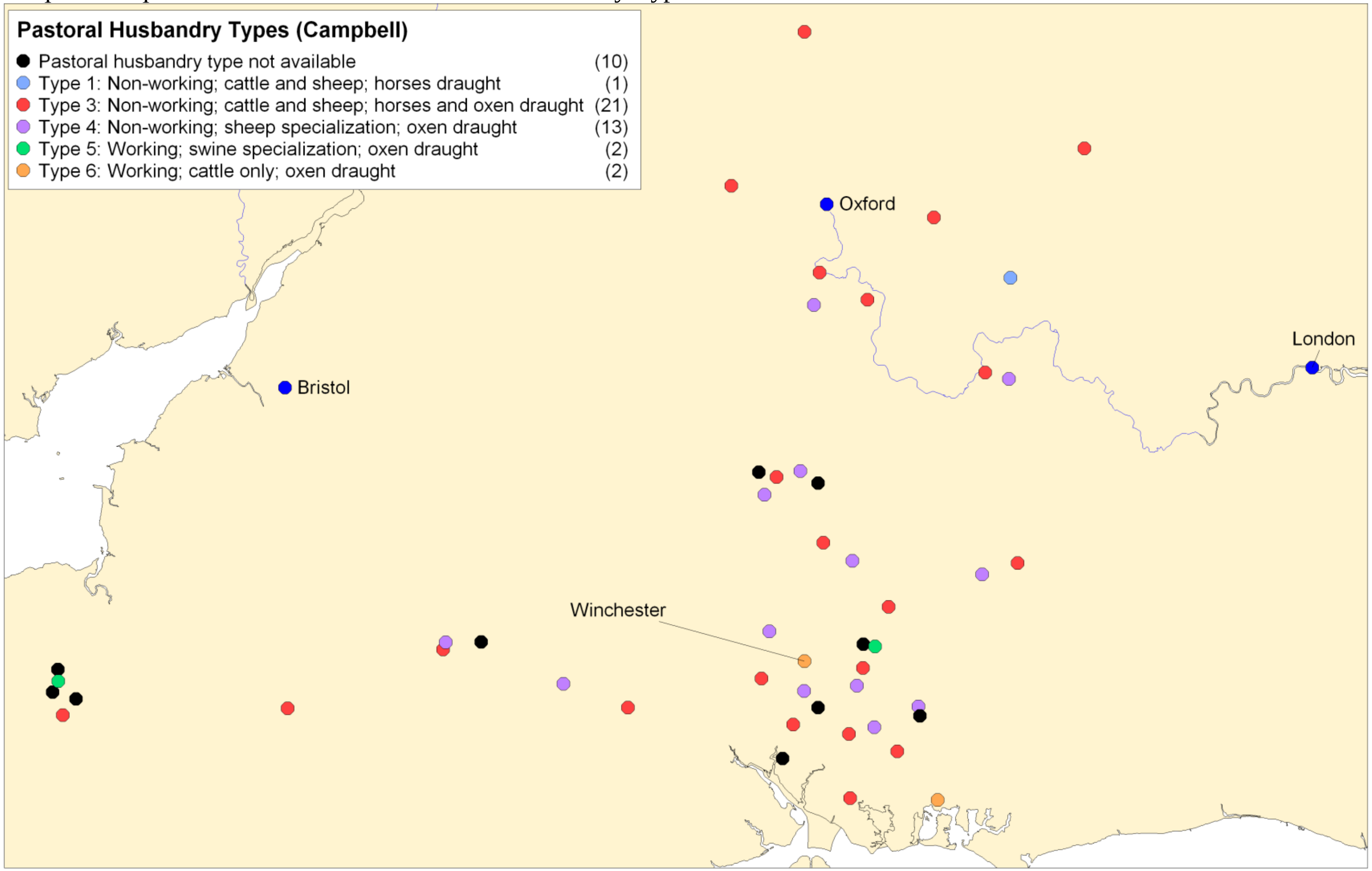


Map 2: Campbell's Post-Black Death Cropping Types



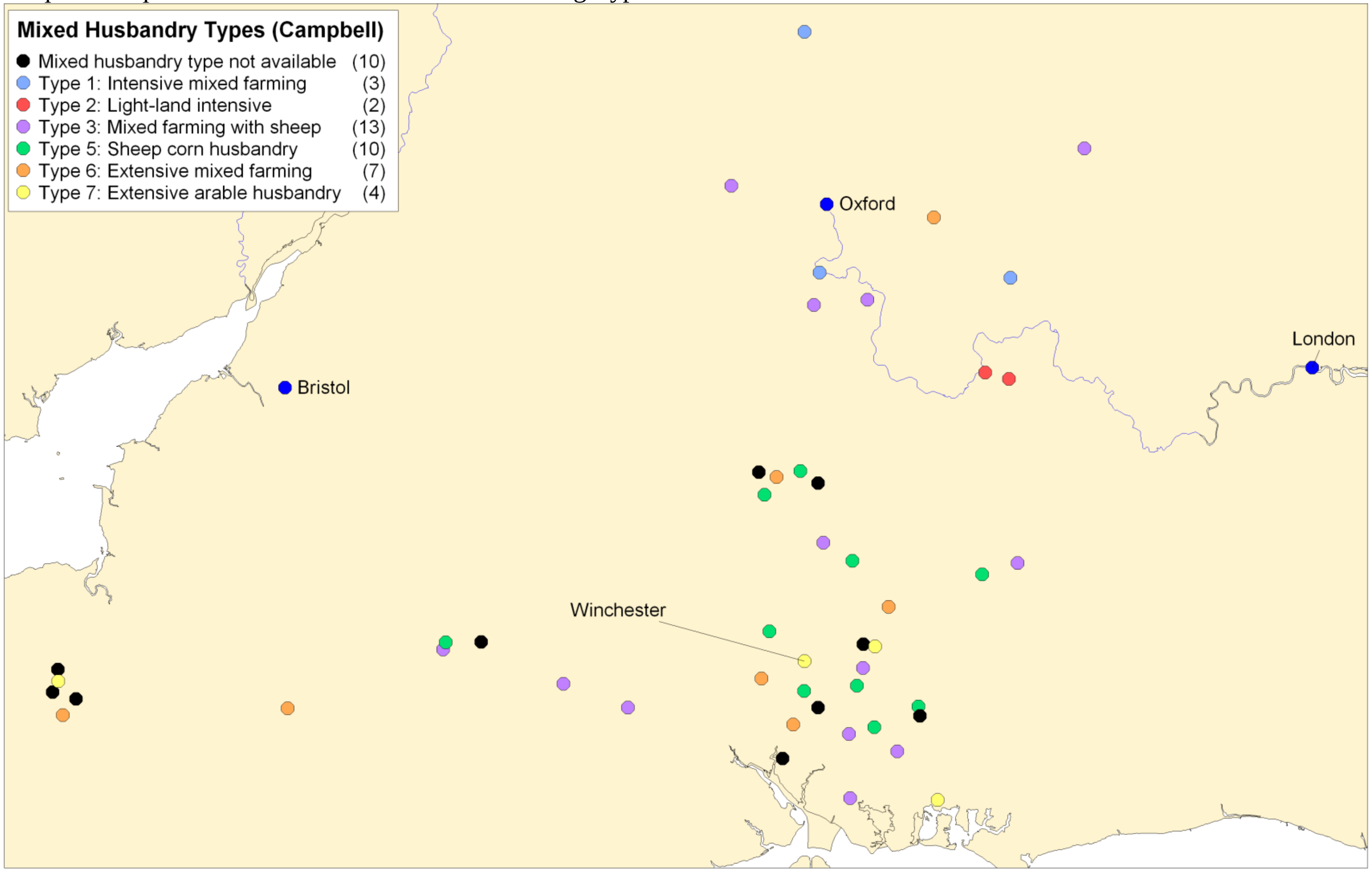
Source: Campbell, *Seigniorial Agriculture*, 441-52.

Map 3: Campbell's Post-Black Death Pastoral Husbandry Types



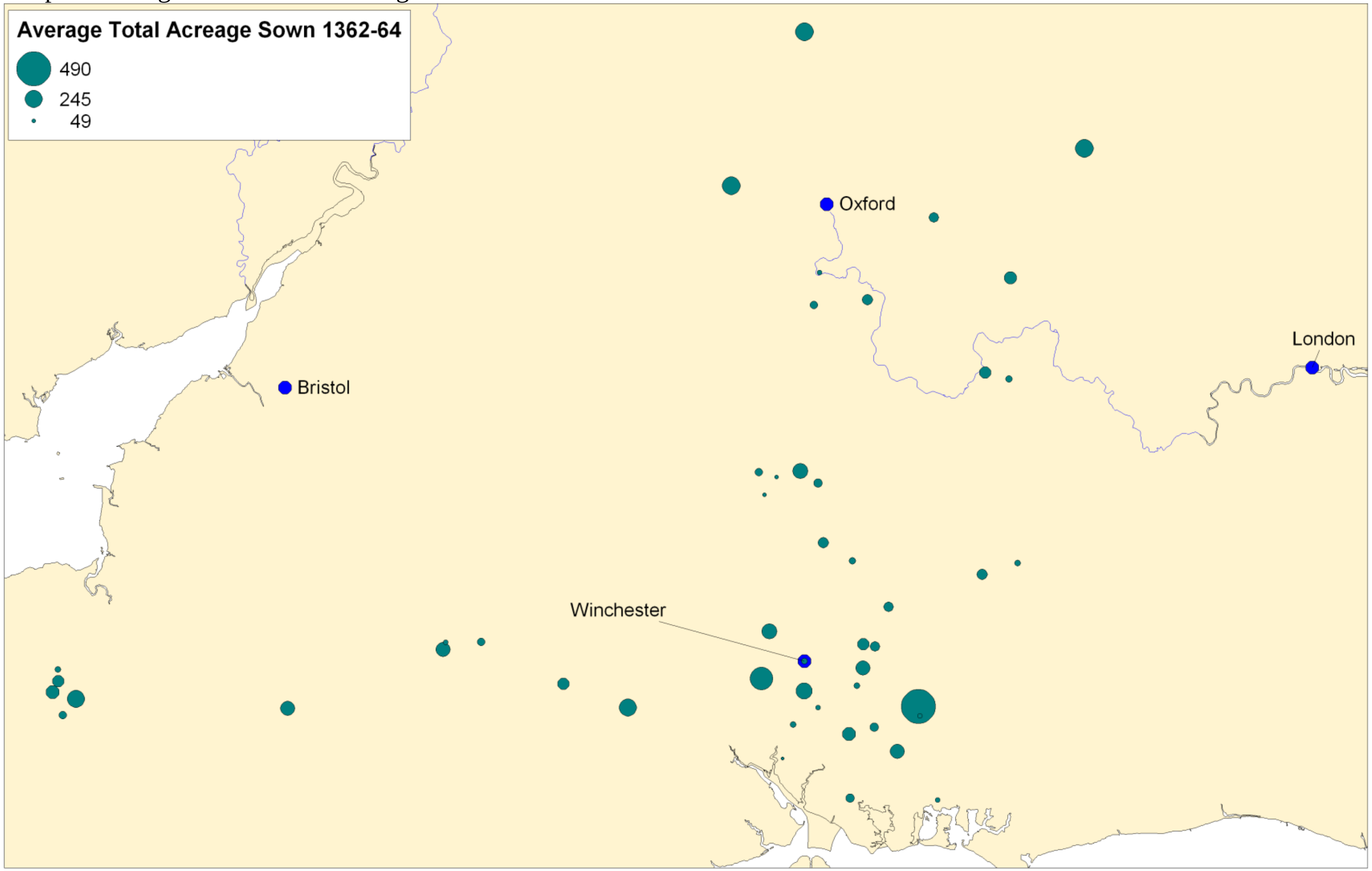
Source: Cambpell, *Seigniorial Agriculture*, 441-52.

Map 4: Campbell's Post-Black Death Mixed-Farming Types

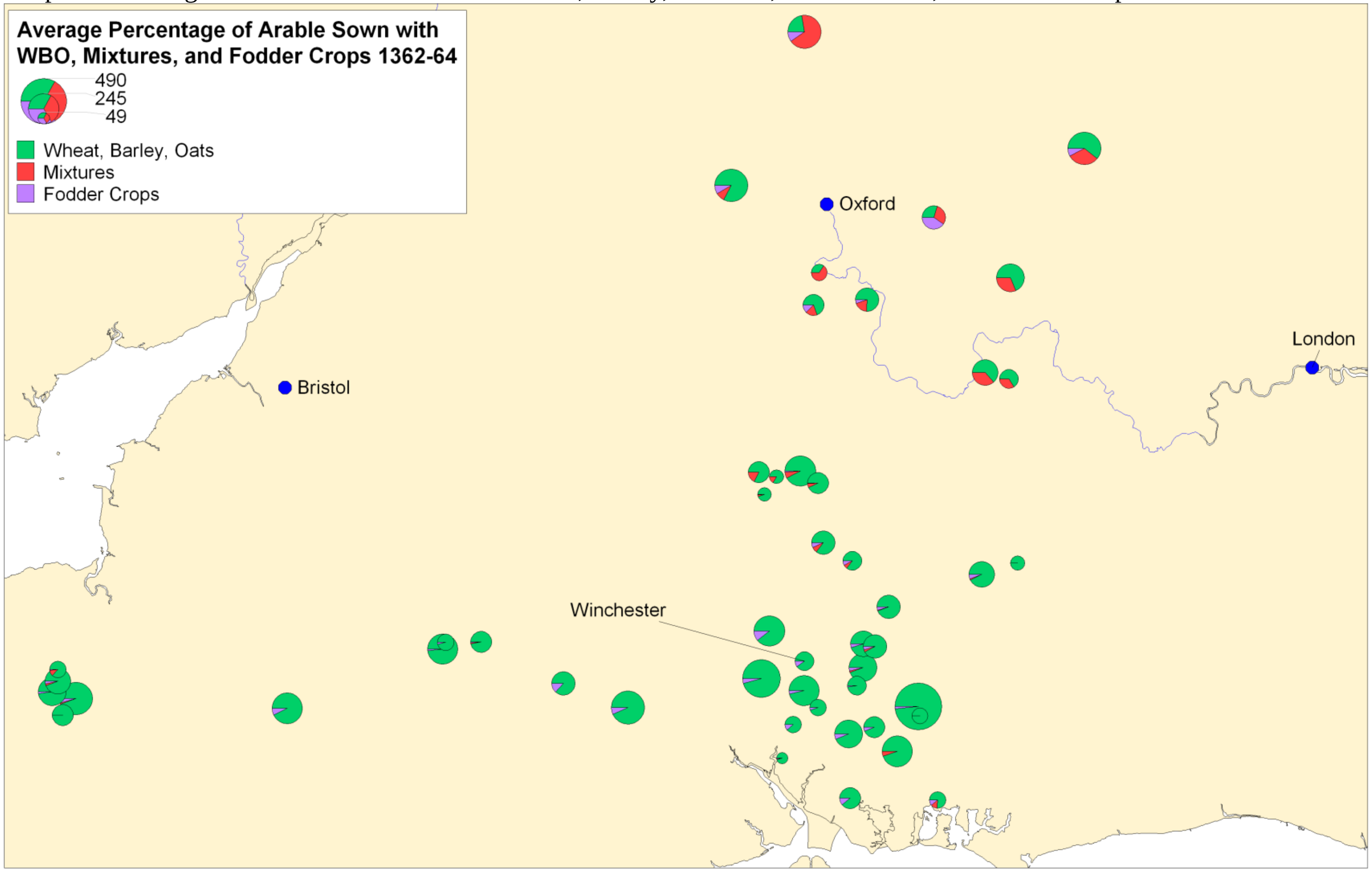


Source: Cambpell, *Seigniorial Agriculture*, 441-52.

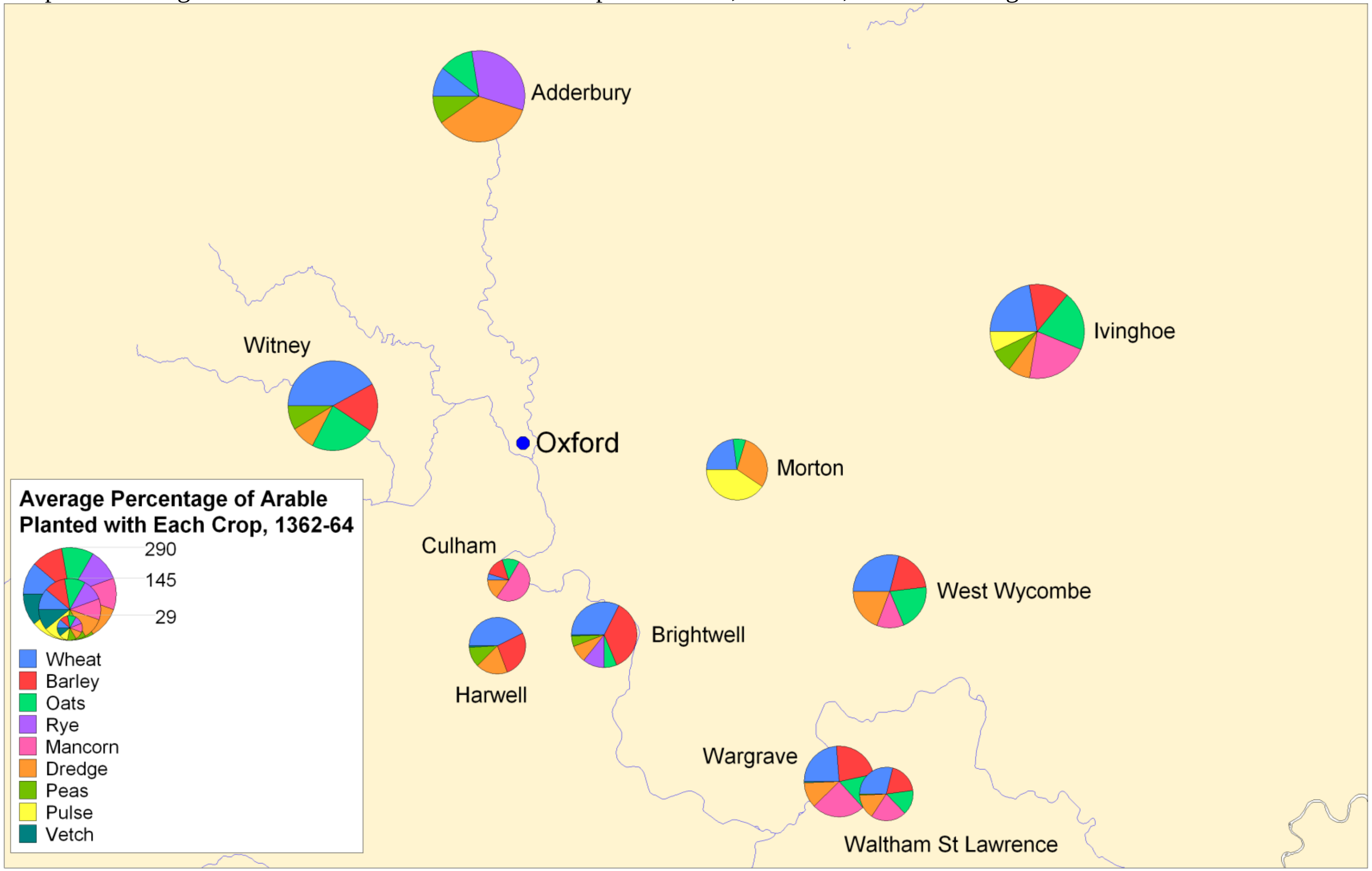
Map 5: Average Total Arable Acreage Sown 1362-64



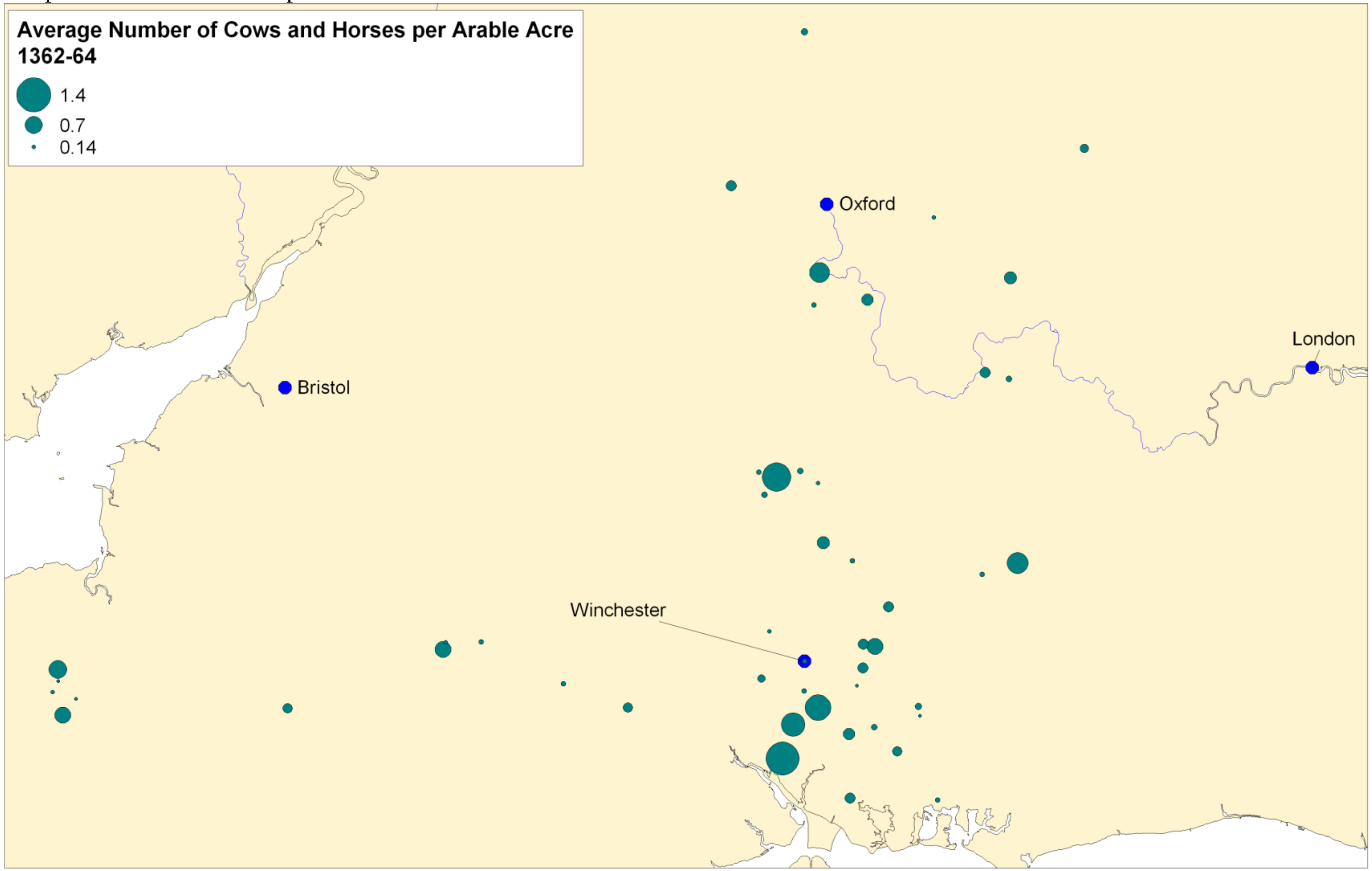
Map 6: Percentage of Arable Land Sown with Wheat, Barley, and Oats; Mixed Grains; and Fodder Crops



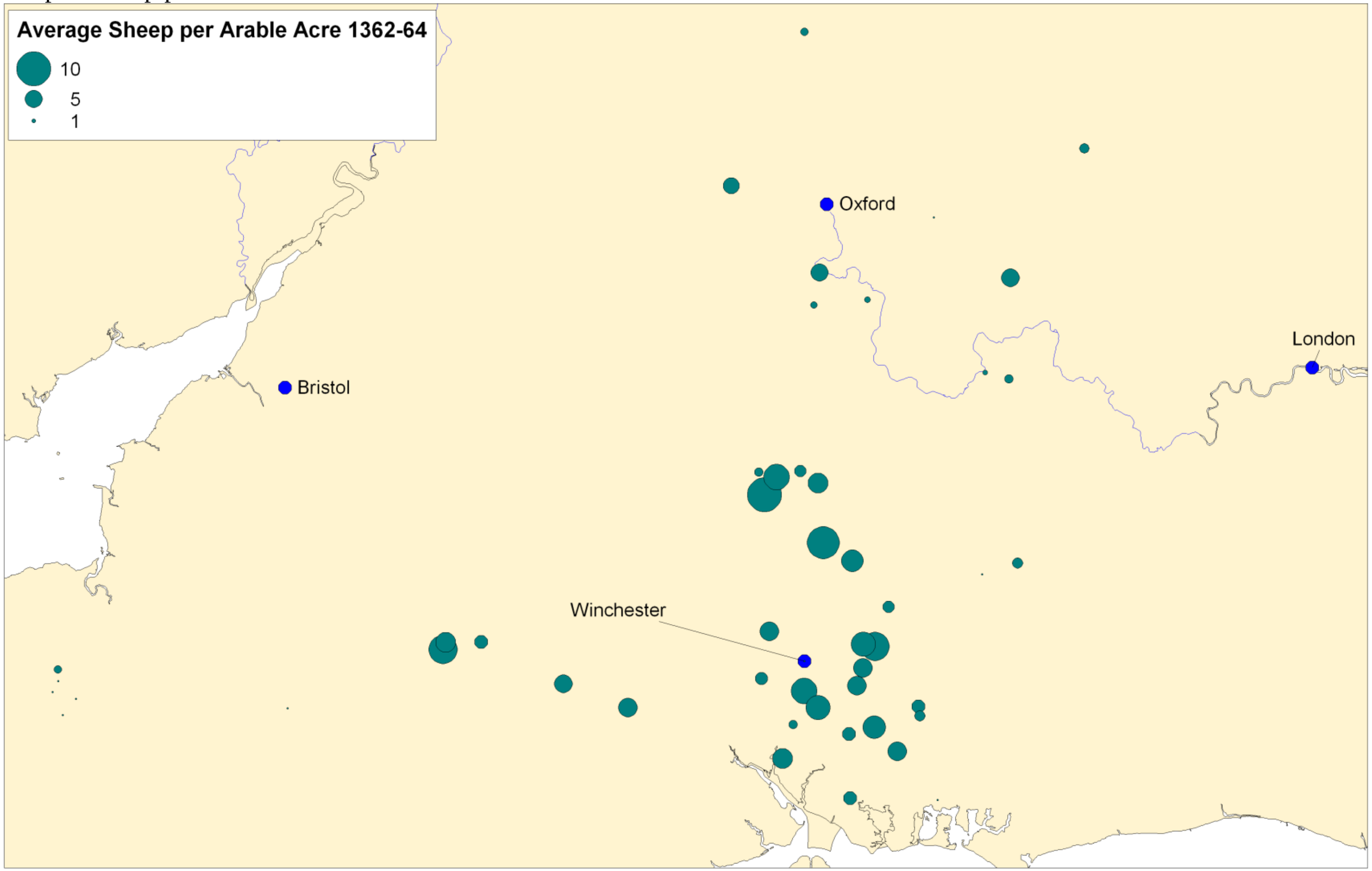
Map 7 Percentage of Arable Sown with Individual Crops – Thames, Chilterns, Cotswolds Region



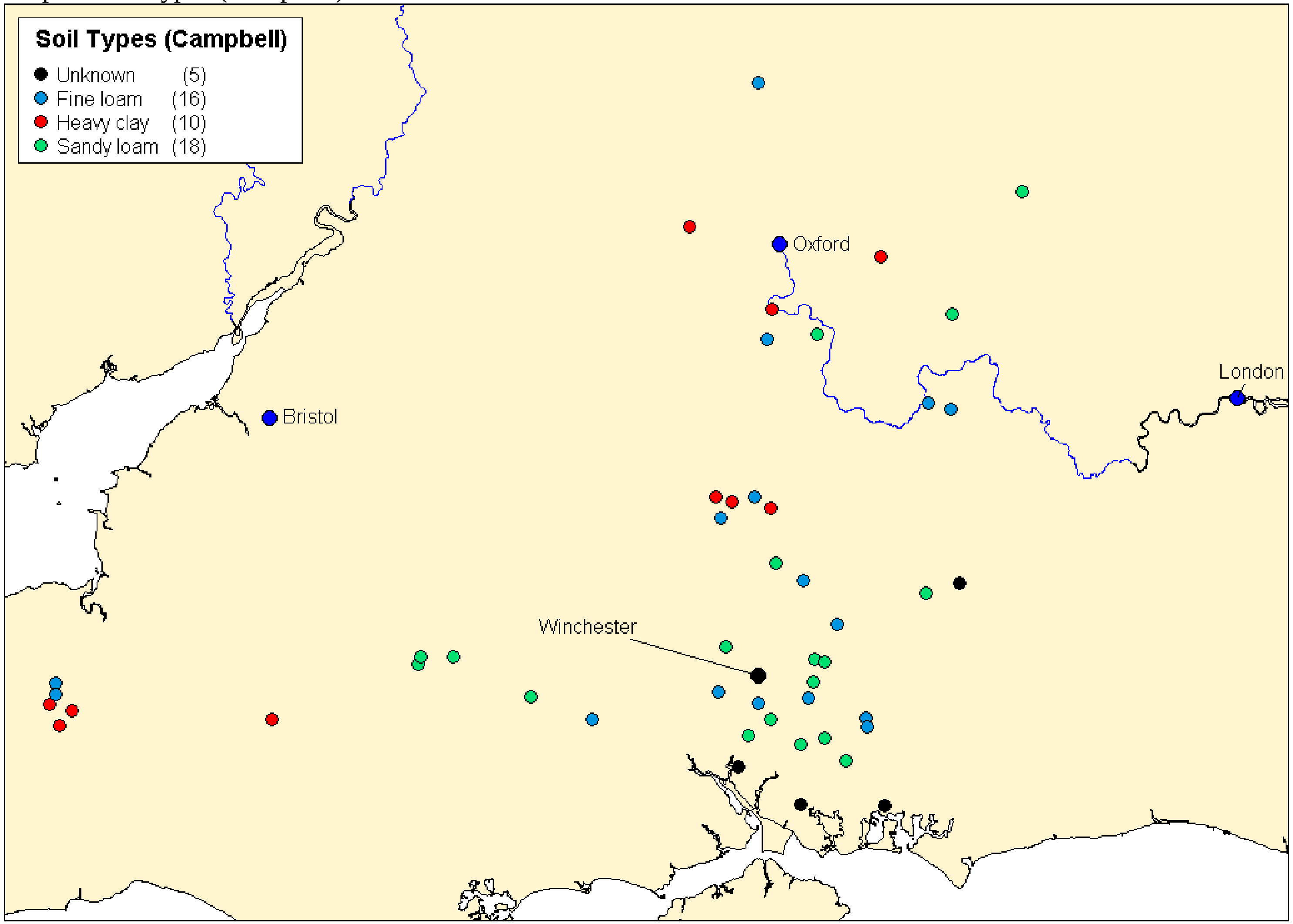
Map 8: Cows and Horses per Acre



Map 9: Sheep per Acre



Map 9: Soil Types (Campbell)



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