

The Origins, Interactions and Causes of the Cycles in Grain Prices in England,

1450–1812

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Abstract

Conventional time series analysis of the English wheat price series, 1450–1812, reveals a short wavelength (period 5–6 years) and a medium wavelength (period 13–16 years) cycle throughout this time, although they developed strongly only at the end of the sixteenth century. The comparable cycles revealed in the series of oats and barley prices are strongly coherent with wheat prices ($p \ll 0.01$), that is the different grain prices responded together. Multivariate analysis and time series analysis show that the medium wavelength oscillation in wheat prices correlates with weather conditions: low winter and summer temperatures are the most significant factors. Both may have a direct effect on the growth and harvesting of the crop, but cold winters may also have indirect effects by establishing a generally cold spring and summer. High winter rainfall is of secondary importance. However, the short wavelength (period 5–6 years) cycle in wheat prices is not significantly correlated with weather and it is suggested that it is driven by economic factors, the short-term effects of a good or bad harvest (autoregressive effects) and possibly by regular epidemics of fungal pathogens of grain. The significance of the 5–6 year oscillation in driving corresponding mortality cycles and of producing cycles of susceptibility which maintained the epidemics of lethal infectious diseases is discussed.

GRAIN prices in past centuries were subject to violent fluctuations from one year to another, although some regularity in the longer-term movement of prices has been discerned. The prime cause of these annual fluctuations has been ascribed to the weather which, in the short run, largely determined the supply of agricultural produce and this dependence on the weather ensured that agricultural prices fluctuated more markedly than other prices. Modern economic systems are provided with a number of built-in stabilizing influences but these conditions were largely absent in England in the sixteenth and seventeenth centuries, and the dramatic fluctuations in grain prices had to be endured as one of the penalties of a backward economic system, in particular the consequence of the inelasticity in demand and supply conditions which distinguished arable agriculture from most other economic activities. In England, drought was normally advantageous to the wheat harvest and, unless prolonged, was

seldom a cause of failure among the other cereal crops because of the predominance of heavy moisture-retaining clay land over lighter sandy soils. However, the disastrous harvest of 1637 was apparently the result of excessive drought. The main danger to cereal crops is believed to be prolonged rainfall in summer accompanied by an almost total absence of sunshine when crops failed to ripen and yields were poor. An excessively cold winter and spring were also harmful to the wheat harvest but had little effect on spring-sown barley, oats and pulses.¹ Wigley and Atkinson² have analysed the mean soil moisture deficit for Kew during the growing season from 1698 and, in contrast with the above, conclude that drought conditions are those that lead to poor crop yields. They suggest that an agricultural drought is determined largely by conditions that lead to stunted growth or even wilting of crop

¹ P Bowden, 'Agricultural prices, farm profits, and rents', in J Thirk, ed, *The Agrarian History of England and Wales: IV*, 1967, pp 617–34.

² T M L Wigley and T C Atkinson, 'Dry years in south-east England since 1698', *Nature*, 265, pp 431–34.

plants; these are a combination of dry soil and a continuing high level of evapotranspiration which the crop is unable to maintain by withdrawing water from the soil. This combination leads to a consistently high soil moisture deficit over the growing season.

Any study of the fluctuations in grain prices is dependent on the pioneering work of Hoskins who provided an analysis, decade by decade, from 1480 to 1759. He suggested that really bad harvests came one year in six, agreeing closely with the popular belief in the sixteenth century that a bad harvest came once every seven years. His examination of harvest sequences revealed no discoverable rhythm and he suggested that good or bad runs were not basically because of weather-cycles, although short-term climatic fluctuations may well have been implicated. He believed that the underlying factor was that of yield ratios in an agrarian economy that worked normally on a very fine margin between sufficiency and shortage. Hoskins has concluded that for the vast majority of the population these short-term fluctuations in the cost of food 'were infinitely more important than the long-term movements to which economic historians have always paid such assiduous attention'.³

The significance of meteorological variables in determining grain prices in Europe has previously been tested for the period between the mid-sixteenth and mid-nineteenth centuries. This modelling was based on monthly estimated measurements of temperature and precipitation and distinguished between weather and non-weather effects. Subsistence crises were triggered by the combination of a cold spring and a rainy midsummer whereas, in the long run, grain prices were more closely

related to the intensity and duration of trade cycles.⁴

Spectral analysis and autoregressive models of agricultural prices in pre-nineteenth-century Europe show that the prices of all cereals and potatoes rose simultaneously in subsistence crises and that regional fluctuations in the prices of cereals existed in Germany because of differences in production, commercialization and consumption practices.⁵

The existence of long wavelength cycles with a period greater than 30 years in the prices of cereals in Europe from the sixteenth to the twentieth century has been studied by statistical analysis. Such cycles would be clearly different from the short-run fluctuations described by Hoskins. Only weak indications of such long waves were found although there was strong evidence of cycles with 10-13 or 15-year periods which seemed to be caused by clusters of unfavourable events in population, climate, structures of production and modes of behaviour. There was no evidence of a relation, as had been suggested, between these medium wavelength oscillations and sunspot activity.⁶

Two theories have been advanced to explain the fluctuations of grain prices: firstly that demand remains constant but rigid and cannot adapt itself to fluctuations in the harvest, and secondly, that the amount of grain offered to the market is subject to fluctuations by producers who consume a certain amount of their own harvest. Subsistence farming and the instabilities of supply and demand must be included in these models of the grain market. During good harvests subsistence farmers reduce their purchases in the market and increase the amount of grain they offer to it; during

³ W G Hoskins, 'Harvest fluctuations and English economic history, 1480-1619', *AHR*, 12, 1964, pp 28-45; *idem*, 'Harvest fluctuations and English economic history, 1620-1759', *AHR*, 16, 1968, pp 15-31.

⁴ C Pfister, 'Fluctuations climatiques et prix cerealiers en Europe du XVIe au XXe siecle', *Ann Econ Soc Civil* 43, 1988, pp 25-53.

⁵ B Roehner, 'Liaison entre les conjonctures de prix des produits de base: le cas de l'Allemagne au XIXe siecle', *Hist and Mes* 6, 1991, pp 31-49.

⁶ R Bos, G van Dijk, C Kruijt and H K Roessingh, 'Long waves in economic development', *AAG Bijdragen, Neth*, 28, 1986, pp 57-92.

bad harvests they increase their purchases in the market and reduce the amount of grain offered. It is concluded that the perceived demand on the market does not reveal as much as the total demand including subsistence farming.⁷

We see from the foregoing that there are considerable differences of opinion concerning the external factors that drive possible cycles in grain prices. Our objective in this paper is to provide an interdisciplinary and statistical study of the annual prices of grains in England from the fifteenth century by time series analysis, a technique that is described in more detail in the next section. By this means, we hope to clarify the most important factors that determined the price of grains and thereby amplify previous work, particularly that of Hoskins, and to provide a framework for future research.

I

In this paper we present the results of a study of the series of national grain indices and prices by time series analysis, a valuable statistical and computing technique for distinguishing and describing cycles (or oscillations) in any long-run data series. It is, therefore, applicable for the quantitative analysis of many aspects of historical demography and has the advantage that a number of conventional programs for use on a PC are available. A very simple oscillating series of grain prices is illustrated, diagrammatically in Figure 1; the time between two successive peaks is termed the wavelength or period (λ) of the oscillation and in the example is obviously 5 years. The frequency of the oscillation is the number of cycles in a standard time, in this case one year. Since the wavelength is 5 years, the frequency is $1/5$ of a cycle per year (ie frequency = 0.2 cycles/year = $1/\lambda$).

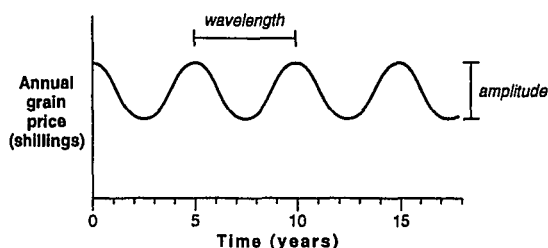


FIGURE 1

Diagram of a very simple oscillation in grain prices to explain the basic characteristics of a cycle in a data series: wavelength (λ , measured in years) = time between two successive peaks; frequency = $1/\lambda$ (measured in cycles per year); amplitude of oscillation (measured in shillings) = difference in grain price between a peak and a trough.

Obviously, grain prices and other real biological and demographic series are more complex; the complications encountered may include: i) the series may be compounded of two or more separate and independent, oscillations; ii) the frequency of any one oscillation may vary over long periods of time; and iii) considerable annual variation may introduce 'noise' which effectively blurs the underlying oscillation(s). An example of the wheat price index, 1450–1600, is shown in Figure 2A which shows a clear change in the long-term trend and in the size (amplitude; see Figure 1) of the oscillations in about 1540.

Although perfect data series are preferred for any study, time series analysis is particularly concerned with the identification of the wavelength and timing of an oscillation and the significance of its correlation with other cycles rather than with the absolute values of the amplitude of the peaks of the cycles. In this way, small variations in grain prices between different regional markets do not affect the overall conclusions of the analysis. In any event, Granger and Elliott⁸ concluded from their study of three different regions in the eighteenth century that the speed of response of prices to changes in

⁷ J-P Simonin, 'Les fluctuations des marches des grains à l'époque moderne', *Hist and Mes*, 5, 1990, pp 181–211.

⁸ C W J Granger and C M Elliott, 'A fresh look at wheat prices and markets in the eighteenth century', *Econ Hist Rev*, second ser, 20, 1967, pp 257–65.

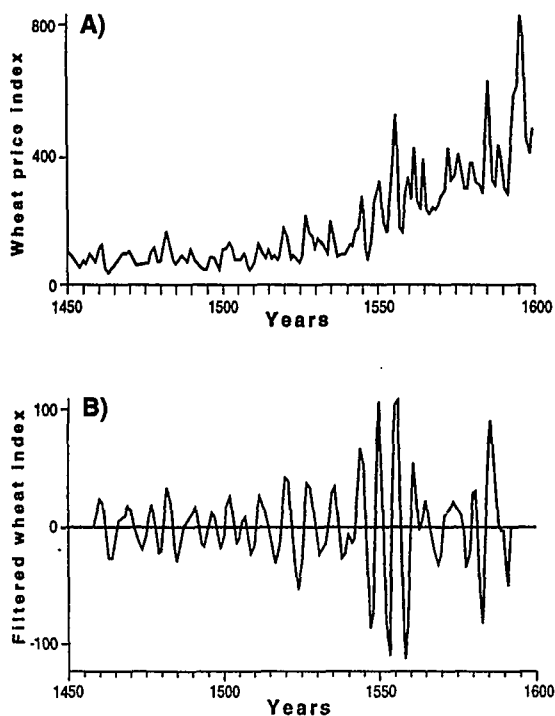


FIGURE 2

National wheat price index early years, 1450-1600. A: unfiltered data series (note rising trend and emergence of short wavelength oscillations during 1550-1600); B: filtered to reveal short wavelength oscillations.

supply and demand was similar and that the three different markets could be treated as one.

A number of different sub-programs are available in time series analysis. Firstly, spectral analysis determines the relative importance and wavelengths of the different cycles contained in the series. An example is shown in Figure 3A wherein four peaks corresponding with four separate cycles are detected in the wheat price series, 1600-1812; the greatest power is shown by the long-term trend (unmarked, wavelength approximately 128 years) and the three other, major cycles are indicated by arrows.

Once an oscillation has been identified, a filter which removes other cycles and noise can be designed and the filtered oscillation at the desired wavelength can be displayed. An example of the filtered,

short wavelength oscillation in wheat prices is shown in Figure 2B.

Coherence and cross-correlation function programs allow the significance of the interrelationships between two oscillations to be determined. For example: does a cycle in seasonal temperatures drive the oscillation in wheat prices? Figure 4C, working with filtered data, shows the strongly negative correlation of the medium wavelength oscillations in summer temperature and wheat prices at zero lag (ie at 0 years), that is, high wheat prices were associated with low summer temperatures in the same year.

In this paper we consider the underlying causes of the grain price cycles in England and have determined i) the origins of the short wavelength oscillation in the wheat, oats and barley series; ii) the interaction between the cycles in the different grain series; and (iii) the effect of weather and other factors in driving these cycles. We show that both a short wavelength and a medium wavelength oscillation can be detected by conventional time series analysis in the national wheat price index, but only the medium wavelength oscillation correlates significantly with weather conditions and we suggest other factors that may contribute to the short wavelength oscillation.

II

Seasonal mean temperatures in central England ($^{\circ}\text{C}$) for 1659-1811 were taken from Manley,⁹ and seasonal rainfall at Kew from 1697-1811 as percentages of the 1916-50 averages were taken from Wales-Smith;¹⁰ winters include the month of December from the previous year. The national grain price indices, 1450-1749

⁹ G Manley, 'Central England temperatures: monthly means 1659-1973', *Q J Roy Meteorol Soc*, 100, 1974, pp 389-405.

¹⁰ E G Wales-Smith, 'Monthly and annual totals of rainfall representative of Kew, Surrey, from 1697-1970', *Meteorol Mag*, 100, 1971, pp 345-62.

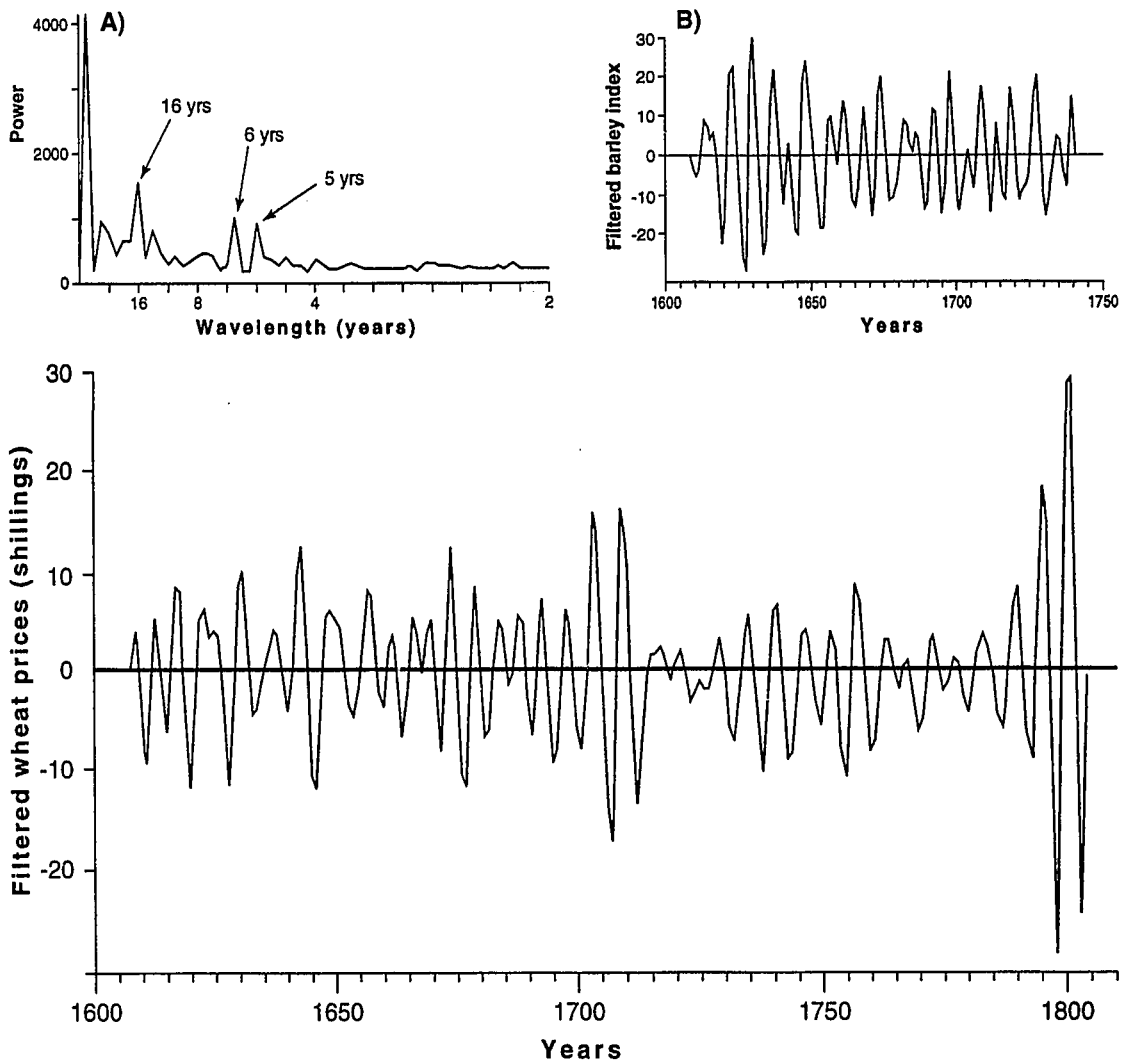


FIGURE 3

Wheat prices (shillings), 1600-1812 filtered to reveal short wavelength oscillations. Insets A: spectrum of data series (note short wavelength cycles 5 and 6 years and medium wavelength cycle at 16 years); B: short wavelength cycles in filtered barley index, 1600-1749.

(wheat, barley and oats) were taken from Bowden;¹¹ the baseline for 1450-1649 was the mean grain price for 1450-99; the baseline for 1650-1749 was the mean value over these years. Absolute wheat prices (shillings), 1600-1812, were taken from Stratton.¹² Time series analysis was carried

out using the program of Shumway¹³ and details of further statistical tests are given in the Appendices.

III

The national wheat price index for the early years, 1450-1600, is shown in Figure 2A and the genesis of the oscillations

¹¹ Bowden, 'Agricultural prices', pp 593-694; P Bowden, 'Price of arable crops', in Thirsk, *Agrarian History: IV*, pp 815-21; and *idem*, 'Agricultural prices, wages, farm profits, and rents', in J Thirsk, ed, *The Agrarian History of England and Wales: V (ii)*, 1985, pp 1-117.

¹² J M Stratton, *Agricultural Records AD 220-1968*, 1970.

¹³ R. H Shumway, *Applied Statistical Time Series Analysis*, Wisconsin, 1988.

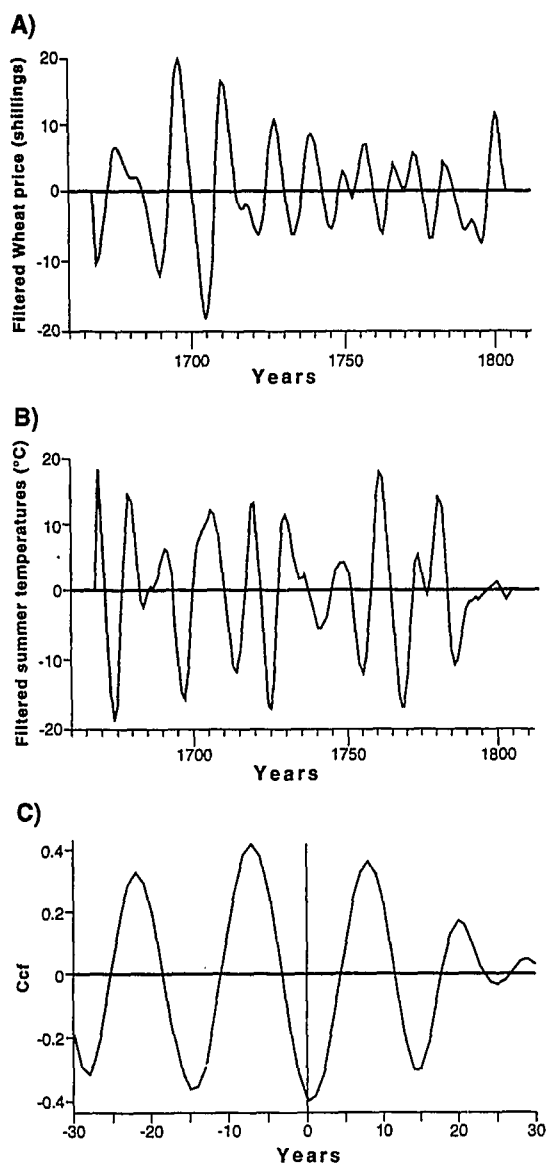


FIGURE 4

Filtered medium wavelength oscillations in wheat prices and summer temperatures, 1659–1812. A: wheat prices (shillings); B: summer temperatures ($^{\circ}\text{C}$); C: cross-correlation function, summer temperatures against wheat prices ($\text{ccf} = -0.4$ at zero lag; abscissa = lag (years)).

can be seen clearly. Before 1550 the cycles were of low amplitude and spectral analysis of this period shows a dominant oscillation of wavelength of 8 years. This low amplitude, short wavelength oscillation is shown

after filtering in Figure 2B. A medium wavelength oscillation in the wheat price index for these early years before 1550 is also detectable; its wavelength varies from 10 to 16 years. After 1550 the earlier stability is lost, the index shows a clear rising trend (Figure 2A) and the oscillations emerge at relatively greater amplitude: spectral analysis of the period 1550–1600 shows a short wavelength oscillation and a weaker medium wavelength oscillation. The emergent short wavelength oscillation after 1550 has a wavelength (or period) of 6 years and is shown after filtering in Figure 2B. In summary, the low-amplitude short wavelength oscillation with a period of 8 years during 1450–1540 changed sharply into a 6-year oscillation with much greater amplitude after 1540, as is clearly shown in Figure 2B.

The two types of oscillation in the wheat price index (short- and medium-wavelength) became more regular and were well-established after 1600. Data for wheat prices (rather than the wheat price index) are available after this date and spectral analysis for the whole of the succeeding period, 1600–1812 (Figure 3A), shows the short wavelength (5 to 6 years) and the medium wavelength (16 years) cycles. The short wavelength oscillation after filtering is shown in Figure 3B; a more detailed analysis of the series shows that the wavelength was predominantly 6 years during the early years (1600–1670) but stabilized thereafter at 5 years (Figure 3). The amplitude of the cycles was reduced during 1710–1790. The strong medium wavelength cycle also found during 1600–1812 is described in greater detail below.

The national indices for oats and barley prices are quoted for the period 1450–1750¹⁴ and their patterns of oscillation corresponds closely with that of the wheat prices (shown in Figure 2) and with

¹⁴ Bowden, 'Price of arable crops', pp 815–21, and 'Agricultural prices', V, pp 1–117.

each other. Thus, prices of both barley and oats also remained steady for the first 100 years (1450–1550) with low amplitude, short wavelength oscillations (period=6 years); after 1550 the index showed a rising trend with the short wavelength oscillations (period=6 years for barley and oats) developing strongly over the next fifty years, corresponding with the pattern in wheat prices. A medium wavelength oscillation with period of 12/13 years was detectable during 1450–1600 in barley prices but not in oats (Table 1). During the period 1600–1750 these oscillations were firmly established and are clearly seen after filtering (filtered barley index shown in Figure 3B). The wavelengths are 7 and 13 years in barley and 6 and 14 years in oats.

IV

The apparent correspondence between the different grain price indices was tested on the raw data on the coherence program and the cross-correlation function was determined from the filtered series. The results are summarized in Table 1 which shows that the oats and barley indices synchronize closely with the wheat series; both are strongly coherent in the short and the medium wavebands ($p < 0.01$). The filtered series synchronize in both the short and medium wavelengths (except for single examples of +1 years and -1 years: see Table 1); the cross-correlation function values confirm the significance of the correspondence. A similar analysis showed that the barley and oats series also strongly cross-correlated. We conclude that the annual price indices of the three grains are strongly interdependent and oscillate together.

This finding confirms previous accounts; Bowden concluded that the short-term movements in the prices of wheat, barley, oats and rye were broadly similar because each grain was in some degree a substitute for the others, while any extremes of cli-

mate in spring or summer affected the yield of all.¹⁵ The graph of the prices of wheat, beans, peas and oats at Lincoln, 1543–1620, shows these commodities moving in close sympathy with each other.¹⁶

V

The possibility that wheat yields and hence prices were influenced by weather conditions during the growing and harvesting seasons has been explored by conventional multivariate regression analysis; data series for seasonal temperature are known from 1659 and for seasonal rainfall from 1697. Analysis of seasonal temperatures (winter, spring, summer and autumn) against wheat prices for the complete period 1659–1811 shows that it is only winter temperatures ($p = 0.046$) that had a significant effect; that is, low winter temperatures are associated with high wheat prices. When this effect of temperature is studied in different periods, the importance and significance of the effect of winter temperature rises: 1659–1780, $p < 0.01$ and in 1700–1750, $p < 0.002$. Additionally, a large negative coefficient was obtained from the analysis for summer temperature, suggesting that low temperatures in this season may affect wheat prices. Multivariate analysis for the period 1659–1780 of winter and summer temperatures shows that both have a significant effect on wheat prices (winter temperatures, $p = 0.01$; summer temperatures, $p = 0.005$). These findings have been confirmed by time series analysis and, in particular, the correlation with seasonal temperatures in the different wavelength oscillations has been explored.

i) *Winter temperatures.* Spectral analysis of the winter temperature data series for the period 1659–1812 shows a dominant medium wavelength oscillation which has a period of 13 years. When the winter

¹⁵ Bowden, 'Agricultural prices', IV, pp 626–7.

¹⁶ Hoskins, 'Harvest fluctuations, 1480–1619', pp 40–41.

TABLE I
Synchrony of short and medium wavelength oscillations in grain prices

Cohort	1450-1550				1550-1600				1600-1750			
Wheat: short medium	Wavelength (yr)				Wavelength (yr)				Wavelength (yr)			
	8 10-16				6 21				6-5 14-16			
Ccf with wheat:	Period (yr)	Lag (yr)	ccf	p	Period (yr)	Lag (yr)	ccf	p	Period (yr)	Lag (yr)	ccf	p
Barley - short	6	0	0.6	0.001	6	+1	0.6	0.001	7	0	0.8	0.001
Oats - short	5	0	0.7	0.001	6	0	0.7	0.001	6	0	0.6	0.001
Barley - medium	12	0	0.5	0.01	13	0	0.5	0.01	13	0	0.9	0.001
Oats - medium	ND	-1	0.55	0.001	ND	-1	0.55	0.001	14	0	0.9	0.001

Upper section of table shows cycles in wheat prices; lower sections shows cross-correlation of identified oscillations in barley or oats prices with wheat prices. Note high significance of coherence between both short and medium wavelength oscillations. Arrows (wheat prices) indicate progressive change of wavelength during 150-year cohort.
Ccf = cross-correlation function. ND (oats) indicates that no medium wavelength oscillations detectable by linear filtering, although good ccf and p values were obtained between the two series.

temperature and wheat price series are filtered to reveal medium wavelength oscillations, they cross-correlate negatively, that is, low winter temperatures are again associated with high wheat prices in the same year.

ii) *Summer temperatures.* Spectral analysis of the annual summer temperature series shows a peak in the medium waveband at 14 years. The coherence program which tests the significance of the correlation between summer temperatures and wheat prices shows that the two series correspond negatively, that is, low summer temperatures are associated with high wheat prices in the medium wavelength oscillation. The association is significant throughout the period 1659–1812 ($p < 0.05$) but is particularly significant during the earlier years, 1659–1780 ($p < 0.01$). Figures 4A and B show the two series (wheat prices and summer temperatures, 1659–1812) filtered to show the medium wavelength cycles; the two series cross-correlate negatively (Figure 4C) confirming the results from the coherence program. We conclude tentatively that these results suggest that, in the medium waveband, both low winter and low summer temperatures are directly associated with poor yields and high wheat prices, with summer temperatures probably having a more significant effect.

iii) *Principal component analysis of seasonal temperatures.* Low (or high) winter temperatures may well affect subsequent spring and summer temperatures and this effect has been tested by principal component analysis and the results are described in Appendix 2. In brief, we conclude from this study that the annual wheat price is correlated with the weather conditions in that year. Multivariate analysis suggests that low winter and summer temperatures have the dominant effect but analysis indicates that low winter temperatures may also be acting indirectly by causing low summer temperatures. Low summer temperatures probably affect harvest yield directly by

causing adverse growing conditions. Thus, time series analysis suggest that these effects of seasonal temperature are detectable in the medium wavelength oscillations of the wheat price series (period about 14 years; Figure 4) but are less strongly associated in the short wavelength oscillations.

iv) *Effect of rainfall and drought conditions.* Multivariate analysis shows that seasonal rainfall had a smaller effect on wheat prices; the significance and values of the coefficients are lower (Appendix 3). However, as Wigley and Atkinson¹⁷ have suggested, it is not the level of precipitation but the soil moisture deficit that may have the greater effect on plant growth. Their data series for mean soil moisture deficits during the growing season at Kew, 1698–1812, has been tested by time series analysis. Spectral analysis shows major peaks at wavelengths of 3 and 5 years; the 5-year oscillation shows weak cross-correlation and coherence with wheat prices but at 1-year lag and with the two series being negatively correlated, that is, low wheat prices were associated with drought conditions, the converse of the expectations of Wigley and Atkinson. We conclude that rainfall and soil moisture deficit had only limited effects on the medium wavelength oscillation in wheat prices.

VI

Spectral analysis of the data series for winter or summer temperatures reveals smaller and secondary peaks of wavelength 5 years in both. These short wavelength cycles also cross-correlate negatively with the corresponding cycle in wheat prices (shown in Figure 3), that is, again low temperatures synchronize with high wheat prices. This finding was confirmed by analysis with the coherence program and we conclude that the short wavelength cycle in wheat prices correlates with these low seasonal tempera-

¹⁷ Wigley and Atkinson, 'Dry years', pp 431–34.

tures but the effect is less marked than in the medium wavelength cycles. As we describe above, a short wavelength oscillation in soil moisture deficits during the growing season (May–August) is detectable but, paradoxically, a good growing season (reflected in low wheat prices) was apparently correlated with drought conditions. We conclude that rainfall and moisture deficits in the soil are of only limited significance in the short waveband.

The multivariate regression analysis program was then re-run including the data on seasonal rainfall and soil moisture deficits in addition to seasonal temperatures but no significant coherence was found in either the medium or short wavelength cycles of the wheat prices and we conclude that winter rainfall has an effect only on a simple annual basis.

VII

Multivariate analysis showed that certain seasonal weather conditions had strong effects on the annual wheat price, particularly on the medium wavelength cycles. Using this analysis it is possible to construct a regression equation which predicts, theoretically, the wheat price in any year, based on the seasonal climatic conditions for that year if it were influenced only by weather (Appendix 3). Thus, the predicted wheat prices have been calculated for the period 1697–1811 in this way and spectral analysis of this theoretical price series (Figure 5A) shows the medium wavelength oscillation, confirming that this cycle in wheat prices can be explained as the consequence of weather conditions. However, spectral analysis of the predicted price series does not show the 5–6 year cycles seen in the real price series (Figure 3); this is considered further in Appendix 3 and it is suggested that the short wavelength cycle (period 5–6 years) may not have been directly linked to climatic conditions and that there were other factors producing

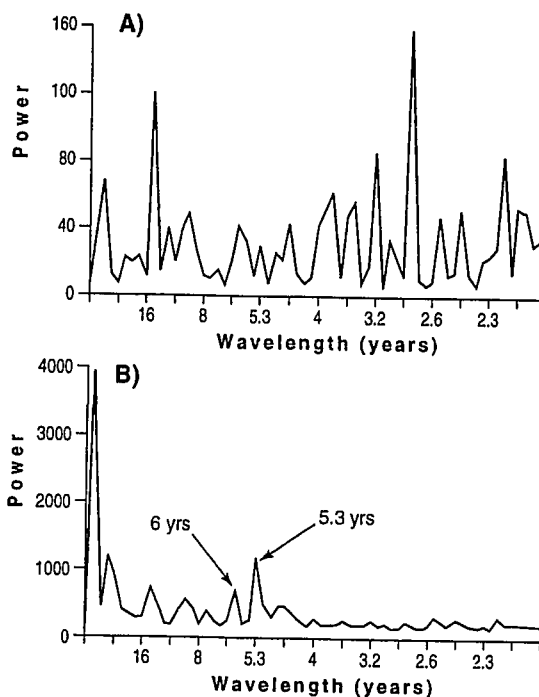


FIGURE 5
Spectrum of predicted wheat prices calculated from regression equation (see Appendix 3). A: predicted wheat prices; B: actual wheat prices minus predicted wheat prices (residuals). Note short wavelength oscillation in residuals at 5 and 6 years.

this oscillation in the wheat price series. It is suggested that wheat prices in the *short term* were influenced for economic and agricultural reasons by the prices declared in the preceding year, the so-called autoregressive effects. This hypothesis was confirmed by re-running the multiple regression of the wheat price series, winter and summer temperatures against wheat prices in the preceding year. The temperatures now have reduced significance whereas the autoregressive term is significant at $p=0.0005$, indicating the 'carry-over' effect of prices into the subsequent year.

There are therefore two different types of cycles in the national wheat price series, medium wavelength (approximately 16 years) and short wavelength (5–6 years); it is the former that is most closely affected

by weather conditions (particularly low winter temperatures) whereas the short wavelength cycles in grain prices are primarily driven by other factors.

VIII

Cycles in the wheat price series. The short and medium wavelength cycles in national wheat prices emerged clearly at the end of the sixteenth century and multiple regression and principal component analyses suggest that weather had a significant effect on prices, presumably via an effect on crop yields. Low winter and low summer temperatures are significantly associated with high wheat prices which presumably are usually associated with poor crop yields. Inspection of the results suggests that the association with winter temperatures is more significant than with summer temperatures, although principal component analysis indicates that its effect may be mainly indirect, that is, a cold winter establishes a cold growing and harvesting season during spring and summer. It has been shown that the colder the winter the greater the month-to-month temperature variability.¹⁸ The significant association of high wheat prices with low summer temperatures is probably direct. The effect of seasonal rainfall appears to be of secondary importance on the medium and short wavebands and is effective only on a simple annual basis, that is, heavy rain at a specific period in summer could ruin a harvest.

However, the present study shows that these effects of weather operate mainly on the medium wavelength oscillation in English wheat prices, whereas the short wavelength oscillation is less significantly related to weather conditions. Comparison of the real annual wheat price index with that predicted from the equation derived from multivariate analysis confirms that the

medium wavelength oscillation, but not the short wavelength oscillation, is driven by weather conditions.

What then are the other causes of the short wavelength cycles in wheat prices? Such an index of prices is partly artificial and is driven by economic factors as well as by grain yields in the fields at harvest time. Cycles in oats, barley and wheat prices were synchronous and oscillated together; if one grain was in poor supply the prices of the others were driven up also. The poor were prevented from substituting cheaper grains and the failure of the crops had a ripple effect that was felt throughout the economy. Appleby also noted that all grains rose symmetrically in price, preventing the labouring poor from switching from their usual bread grains to cheaper grains and thereby staying alive.¹⁹ Harrison also recognized that in years of high prices all prices rose, although not to the same extent.²⁰ Obviously, major transient (non-cyclical) weather events can contribute to a bad harvest in any one year (eg scorching of the oats crop in Lancashire in 1762). Hoskins²¹ suggested that the cyclical disposition of grain prices was not basically because of weather-cycles but to the underlying factor of yield-ratios.

One bad harvest, by reducing the yield ratio to dangerously low levels, tended to generate another because of the scarcity of seed-corn, and it has been suggested that this effect was cumulative until a change in the weather pattern broke the sequence and restored the normal balance between bread-corn and seed-corn.²² Wrigley²³ noted the relationship between grain prices and the size of the harvest and suggested

¹⁹ A B Appleby, 'Grain prices and subsistence crises in England and France, 1590-1740', *J Econ Hist*, 39, 1979, pp 865-87.

²⁰ C J Harrison, 'Grain price analysis and harvest qualities, 1465-1634', *AHR*, 19, 1971, pp 135-55.

²¹ Hoskins, 'Harvest fluctuations, 1620-1759', pp 17-18.

²² Hoskins, 'Harvest fluctuations, 1620-1759', pp 17-18; Bowden, 'Agricultural prices', IV, p 634.

²³ E A Wrigley, 'Some reflections on corn yields and prices in pre-industrial economies', in J Walter and R Schofield, eds, *Famine, Disease and Social Order in Early Modern Society*, 1989, pp 235-78.

¹⁸ S W Tromp, *Biometeorology*, 1980.

that fluctuations in price may reflect the level of grain stocks carried over, varying with the abundance of the harvest, and not on the runs of deficient and abundant harvests.

These are so-called autoregressive effects in which the grain price is strongly influenced by the price in the preceding one or even two years. An autoregressive term included in the multiple regression in the present study (see above and Appendix 1) is highly significant ($p=0.0005$) and a second autoregressive term is also significant ($p=0.012$) showing that the wheat prices in the two preceding years have detectable effects.

The closer the farmer operates at subsistence level, the larger the number of years in which he will have no surplus to sell and must therefore enter the market as a buyer at high prices. For the sixteenth and seventeenth centuries, the English agrarian economy operated on a very fine margin between sufficiency and shortage, and where a society consumed almost all of its annual output within a year, fluctuations in the harvest must have possessed overriding economic significance. Such economic factors could have made a major contribution to the clear short wavelength oscillation in grain prices that emerged strongly at the end of the sixteenth century, but it seems that other regulatory mechanisms were probably implicated in generating such a regular oscillation.

Rust and other parasitic infestations of grain crops. Fungal diseases such as mildew, loose bunt and rust were the major scourge of cereals and frequently destroyed whole crops. Periodically, severe and chronically damaging cereal rust epidemics have plagued mankind. Could these fungal diseases be a contributory factor to the short wavelength oscillations observed in grain prices? Rust has the ability to cycle between alternate hosts and, like other fungal diseases, can display endemic and epidemic conditions.

If conditions remain constant from year to year, the fungal epidemic will settle down and the infection rate will remain constant but any departure from uniformity would cause an increase in infectivity and the threat of an epidemic. For instance, depleted stocks of seed corn following a fungal epidemic and a deficient harvest would decrease the amount of plant host available to the pathogen during the next season. Each year without an epidemic would increase the proportion of seed corn available for planting and the number of susceptible host plants, until conditions were suitable for an explosive epidemic resulting in a much reduced crop yield. In this way, the process would be self-perpetuating and these 'boom and bust' cycles have been described and account for many of the most damaging epidemics of cereal diseases.²⁴

During the early periods of agriculture of the seventeenth and eighteenth centuries, the outbred wheat would show wide genetic variability with differing degrees of susceptibility to fungal attack; one of the major ways of developing this protection is by a thickened cuticle to prevent fungal entry. The farmer would, unconsciously, use a form of selective breeding in that the seed corn from a harvest during a severe fungal attack would, inevitably, tend to come from the resistant varieties of wheat plants that had survived to maturity. Consequently, a greater proportion of resistant grains would be sown and resistant plants would be harvested in the following year. However, the fungus would, in turn, have been developing more active penetrant strains and so the boom and bust cycle of fungal epidemics would tend to develop. Severe rust epidemics would be less likely to recur the year following an outbreak and they would have an inherent periodicity dependent upon the time taken to

²⁴ R. G. Priestley, 'Detection of increased virulence in populations of wheat yellow rust', in P. R. Scott and A. Bainbridge, eds, *Plant Disease Epidemiology*, 1978.

build up a sufficient number and density of susceptible hosts.

We suggest, therefore, that the regular short wavelength cycle in grain prices was not greatly affected by cycles in the weather (unlike the medium wavelength oscillation) and that the peaks of the oscillations were sharpened by economic and autoregressive factors and possibly by regular epidemics of fungal diseases.

The effect of oscillations in grain prices on population dynamics. The question of the effects of food supply, famine and malnutrition on the demography of England in earlier centuries has been considered in detail by Livi Bacci.²⁵ Here we are specifically concerned with the subliminal effects of the short wavelength oscillation in wheat prices (period = 5–6 years) on the population dynamics of single communities. We have shown that in the period 1550–1812 (when parish registers provide an excellent data base for the study of population dynamics in a single community) a short wavelength mortality cycle can be detected by conventional time series analysis in the parish of Penrith, Cumbria, and in other parishes. These mortality cycles synchronize and cross-correlate with the short wavelength cycle in the grain prices; high wheat prices are associated with high mortality. The community at Penrith from 1550–1750 was living under marginal conditions and experienced poor nutrition and even famine; the population was in steady-state under density-dependent control and

was particularly sensitive to fluctuations in the quality and quantity of the food supply.²⁶ Neonatal and postneonatal mortality cycles correlated closely with wheat prices during pregnancy or during the first year of life respectively.²⁷ Furthermore, smallpox developed as a lethal disease after about 1650 and the community at Penrith experienced regular five-yearly epidemics which synchronized with the peaks of the cycles in wheat prices.²⁸ However, the 5–6 year oscillation in grain prices has been shown to have more far-reaching effects: it caused a corresponding oscillation in susceptibility which sustained the regular epidemics of lethal infectious diseases such as smallpox and whooping cough in London and other large cities in the seventeenth and eighteenth centuries.²⁹ These findings confirm the conclusion of Hoskins that for the bulk of population the short-term fluctuations in the cost of food were much more important than the longer-term movements of grain prices.³⁰

²⁶ S R Duncan, S Scott and C J Duncan, 'Time series analysis of oscillations in a model population: the effects of plague, pestilence and famine', *J Theoret Biol*, 158, 1992, pp 293–311.

²⁷ S Scott, S R Duncan and C J Duncan, 'Infant mortality and famine: a study in historical epidemiology in northern England', *J Epid Comm Hlth*, 49, 1995, pp 245–52.

²⁸ S R Duncan, S Scott and C J Duncan, 'An hypothesis for the periodicity of smallpox epidemics as revealed by time series analysis', *J Theoret Biol*, 160, 1993, pp 231–48.

²⁹ S R Duncan, S Scott and C J Duncan, 'The dynamics of smallpox epidemics in Britain 1550–1800', *Demography*, 30, 1993, pp 405–23; *idem*, 'Modelling the different smallpox epidemics in England', *Phil Trans Roy Soc B*, 346, 1994, pp 407–19; *idem* 'Smallpox epidemics in cities in Britain', *J Interdiscip Hist*, 25, 1994, pp 255–71; C J Duncan, S R Duncan and S Scott, 'Whooping cough epidemics in London, 1701–1812: infection dynamics, seasonal forcing and the effects of malnutrition', *Proc R Soc Lond B*, 263, 1996, pp 445–50.

³⁰ Hoskins, 'Harvest fluctuations, 1620–1759', p 20.

²⁵ M Livi Bacci, *Population and Nutrition*, 1991.

APPENDIX 1

Non-stationarity in the wheat price series

Possible problems with non-stationarity were addressed as follows. For a signal to exhibit weak stationarity it has to satisfy two criteria: i) the mean remains constant and ii) the autocorrelation function (acf) remains constant (ie they are both independent of time). The programs employed, including the coherence procedure, involve

detrending so that the mean equals 0. These analyses therefore satisfy criterion i) above. Where the acf does not remain constant over long periods of time, the data series have been subdivided into cohorts and the short-wavelength oscillations were found to have a stable acf and the cross-correlation and coherence tests have been applied to the cohort. Finally, the series have been filtered specifically to

remove periodic factors. The wheat price series can be described by the following equation:

$$\begin{array}{llll} \text{wheat}(t) = \mu - \alpha_1 & \text{winter} & \text{temp}(t) - \alpha_2 & \text{summer} \\ \text{temp}(t) - \alpha_3 & \text{autumn} & \text{temp}(t) + \alpha_4 & \text{winter} \\ \text{rain}(t) + \alpha_5 & \text{summer} & \text{rain}(t) + \alpha_6 & \text{autumn} \\ \text{rain}(t) + \eta(t) & & & \end{array}$$

where $\eta(t)$ is non-white noise. Analysis of the residuals indicates that they can be modelled by an ARIMA process, driven by white noise,

$$\eta(t) = \beta_1 \eta(t-1) + \beta_2 \eta(t-2) + e(t) - e(t-5)$$

where $\beta_1 = 0.72$ and $\beta_2 = -0.006$ and where $e(t)$ is white at the 99.5 per cent level (Box and Pierce test). We conclude that the major non-stationary term is the periodic component of wavelength five years, the short wavelength oscillation.

APPENDIX 2

Principal component analysis of the interaction of seasonal weather conditions

The major effect of a cold winter might be to cause a generally cold growing and harvest year, rather than a direct effect on the crop. When the spring temperature data series is regressed on the winter temperature series as predictor, the two files are significantly correlated ($p < 0.0005$). The summer temperature series is also significantly correlated with winter temperatures, $p = 0.006$. Autumn temperatures are not correlated with winter temperatures. Thus, the association between high wheat prices and low winter and summer temperatures, shown above, may indicate a sensitivity of the prices to a generally cold year.

This possible interaction of the independent variables has been checked by principal component analysis of the annual data series of the four seasonal temperatures. Only principal component 1 (PC1) had an eigenvalue (variance) > 1 which accounts for 53 per cent of the total variance; the coefficients of PC1 were winter = 0.862, spring = 0.401, summer = 0.232, autumn = 0.206. When the component score, calculated from the co-variance matrix, is regressed with the wheat price series, only PC1 is significant ($p = 0.019$). We conclude

from principal component analysis that the annual wheat price is correlated with the weather conditions in that year. Multivariate analysis suggests that low winter and summer temperatures have the dominant effect but the coefficients of PC1 indicate that low winter temperatures may also be acting indirectly by causing low summer temperatures.

APPENDIX 3

Predicted wheat prices series

Multivariate analysis shows that spring rainfall and spring temperature were completely without significant effect on wheat prices. Consequently, the analysis was re-run with these two variables omitted; the analysis of variance now shows that the overall regression is significant ($p < 0.001$). The predicted wheat price can be determined from this analysis as follows: wheat price (shillings) = $79.9 + (0.027 \times \text{summer rain}) + (0.0262 \times \text{autumn rain}) + (0.0783 \times \text{winter rain}) - (2.05 \times \text{summer temperature}) - (0.48 \times \text{autumn temperature}) - (3.61 \times \text{winter temperature})$. Note the high coefficients (and relative importance) for summer and winter temperature.

The regression equation can be used to predict the annual wheat price if it were influenced only by weather, and the predicted wheat prices are calculated for the period 1697-1811 from the derived coefficients and the annual mean seasonal temperatures and rainfall for that year. Spectral analysis of this calculated series shows dominant oscillations of 3 years and 14 years (Figure 5A), but does not show the 5-6 year cycles seen in the real price series (Figure 3A). The predicted and real wheat price series were coherent in the 8-16 year ($p < 0.025$) and the 3-year waveband ($p < 0.05$) suggesting that these cycles in wheat prices can be explained as the consequence of weather conditions.

When the predicted annual wheat prices are deducted from the real prices, the resulting data (residuals) should represent those factors that were less related to climatic factors. Spectral analysis of this recalculated series now shows a 5-6 year cycle (Figure 5B) and it is suggested that this short wavelength cycle in prices may not have been directly linked to climate.

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