Long-Term Fluctuations in Climate and Population in the Preindustrial Era

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The relationship between climatic change and population growth over the long term has been a subject of interest and speculation among historians, economists, climatic historians, anthropologists, geographers, and demographers alike. That variations in climate could affect population growth is an intriguing proposition since climate is one of the few unarguably exogenous variables available to those interested in modeling long-term preindustrial population movements. In their quest to explain long-term variations in vital rates, demographers have generally relegated their discussion of climate to a sentence or two. Though admitting climate as a possible explanatory variable, they devote most of their attention to hypotheses and analyses concerning technological development, microorganisms, real wages, nuptiality valves, Malthusian equilibriating mechanisms, risings of the rural proletariat, and combinations thereof, generally accompanied by complex homeostatic models. This article examines the possible impact of climatic fluctuations on preindustrial population over the long term, thereby contributing to the analysis of a relationship that I hope to show deserves more than passing attention.

The hypothesis under consideration is that long-term changes in middle latitude climate have had a significant impact on long-term variations in population size in middle latitude preindustrial societies. In what follows, I propose a model representing the relationship between climatic change and population growth. I evaluate evidence for climatic change, examine the connection between climatic change and fluctuations in food supply, and explore the effect of climatic change on vital rates. I then subject this model to empirical analysis, using data from various European countries, China, and a number of archaeological sites in North America and Europe.

Historians have speculated on the possible relationship of climate with human affairs. Utterström (1955), one of the first scholars to consider seriously the effect climate might have on population, set the stage for future work by outlining the likely impact climate had on historical events, especially in Scandinavia. Lopez (1967), Parker and Smith (1978), Parker (1979), Davis (1973), and Braudel (1973) have also suggested that climate may have been an important factor affecting preindustrial populations.

In reference to the global scale of fourteenth century demographic crises, Lopez suggests that "Information on climate, though less scanty for the 14th century than for the 4th, is woefully inadequate and ill-explored. Still, what little we know seems to indicate at that period both the crest of a 'pulsation' (that is, of a slow fluctuation stretching over several centuries) and a number of short-run deviations which sharpen the effect of the basic trend" (1967: 396).

In his study of the worldwide political, economic, and demographic crises of the seventeenth century, Parker concludes: "All evidence, whether gathered by historians, meteorologists or solar physicists, points to climate of greater extremes of weather, and in particular to cooler and wetter summers in the temperate zone, during the seventeenth century, with a particularly severe period between 1640 and 1660" (1979: 21). He attributes the unusual climatic conditions to variations in solar radiation (1979: 19).

Davis, analyzing the development of the Atlantic economies, suggests that "The changing climate, apparent in the slow worsening and the slow improvement, over many decades, of the 'average' weather conditions around which each year's weather fluctuated, was a factor of the utmost economic importance which is only now beginning to be cautiously approached by historians" (1973: xii).

Braudel, puzzled by the global expansion and increase in population in the eighteenth century, asks why these phenomena occurred "at the same time throughout the world when space had always been available? The simultaneity is the problem. The international economy, effective but still so fragile, cannot assume sole responsibility for such a general and powerful movement. It too is as much consequence as cause. One can only imagine one single general answer to this almost complete coincidence: changes in climate" (1973: 18).

Regarding the global nature of the "crises" of the mid-second millennium B.C., the fourth and fifth centuries A.D., the fourteenth century, and the seventeenth century, Parker and Smith note, "the world-wide extent of these upheavals suggests that, beneath the obvious local causes, some very basic and deep-seated influences were at work, such as a general deterioration of the global climate leading to relative over-population and food shortages, to mass migrations (perhaps armed) from poorer to richer lands, to swift-spreading pandemics, and to frequent wars and rebellions" (1978: 4).

Le Roy Ladurie (1971) examined evidence purporting to show some connections between climate and history but rejected the hypothesis because of the lack of sufficient quantitative evidence. However, research in this area has expanded in the past few years, providing a mass of quantitative meteorological and demographic material directly applicable to the analysis of long-term variations in climate and population. A number of recent works are devoted to the issue of climate and history, including studies by Rotberg and Rabb (1981), Wigley, Ingram, and Farmer (1981), Lamb (1982), Harding (1982), and Libby (1983).

Not surprisingly there still exists a wide range of opinion about what effect, if any, climate has on history in general and on population in particular. I propose to develop theoretically and support empirically a model capable of delineating the various mechanisms by which climate might have affected preindustrial populations.

Climate and population size

The hypothesis under consideration is simply that long-term fluctuations in population size about the secular trend are largely a result of long-term fluctuations in climate. Warm periods are associated with above-average population levels, cool periods with below-normal levels. The application of the theory is limited to preindustrial populations (before 1800) in middle latitude areas. These areas include most of the Eurasian land mass, most of North America, and the southern portions of Africa, Australia, and South America.

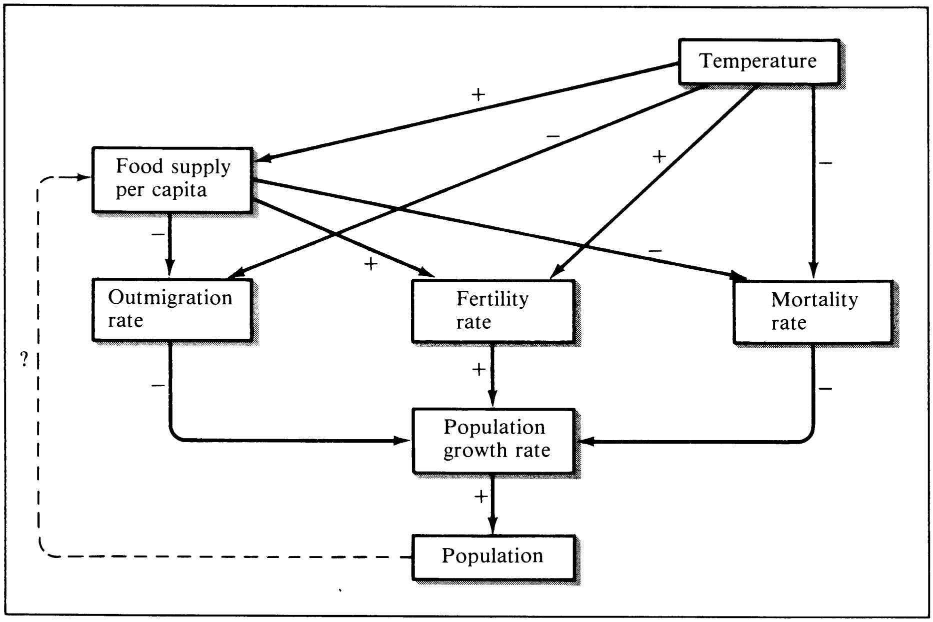
The model is presented in schematic form in Figure 1. Although the diagram may appear at first glance to be complicated, it is actually straightforward. Long-term fluctuations in middle latitude temperature cause long-term fluctuations in food supply per capita and in vital rates. Food supply per capita and temperature independently affect vital rates. The vital rates determine the rate of population growth, which by definition affects the level of population.

The cause of observed long-term variations in middle latitude temperature is under debate. The notion is generally accepted that temperatures did vary over the long run in close synchrony across most areas in the middle latitudes (Gribbin and Lamb, 1978: 81; Williams and Wigley, 1983: 299). Whether this was caused by solar activity (Eddy, 1977a, 1977b, 1981; Libby, 1983: 46; Sonett and Suess, 1984: 141–143), volcanic activity (Dansgaard, 1981: 193–206), or some other natural phenomenon is of little consequence to this study since the temperature proxy series, where they overlap, are generally highly correlated. The mechanisms involved must be left to the climatic historians and solar physicists to determine (Lamb, 1982: 49–66; Sonett and Suess, 1984: 141–143; Herman and Goldberg, 1985: 1–172).

The long-term fluctuations in food supply per capita suggested by the model consist of two components, one exogenous, the other endogenous. The exogenous component is the impact of long-term climatic variations on long-term fluctuations in carrying capacity independent of the impact of human agency.

Long-term fluctuations in population size, the endogenous component, may affect long-term variations in food supply per capita. The effect can be negative according to Malthus (1798: Chapter 1), positive according to Boserup

FIGURE 1 Model for long-term fluctuations in climate and population in a middle latitude preindustrial society



NOTES: The arrows may be read as follows: "Long-term fluctuations in *X* are associated with long-term fluctuations in *Y*." The sign indicates whether the association is positive or negative. Only the important "causal" connections are shown.

(1981: 5–7), or sometimes positive and sometimes negative, as suggested by Lee (1984: 1). Support for any of these positions depends to a certain extent on how one assesses the magnitude of the impact of technological innovation, a thorny issue that is difficult to resolve empirically (Lee, 1984 and 1985). These uncertainties are suggested by the question mark that accompanies the dashed line in Figure 1. This study will not take a position on the possible impact of population size on long-term variations in per capita food supply. Assessment of the magnitude of this impact, if any, must be left to future research. The point is that variations in food supply per capita may be affected by population size and technological change. However, the magnitude of these induced variations will be reinforced or dampened (depending on the timing of the events relative to climatic change)—and possibly overwhelmed—by the exogenous forces of climate on carrying capacity over the long term.

An implication of the proposed model is that periods of cooling will have a positive impact on population growth in characteristically hot regions—for example, the desert regions of the southwestern United States. This possibility will not be explored further in this study due to the lack of sufficient meteorological and demographic data for these areas.

Long-term fluctuations in middle latitude climate

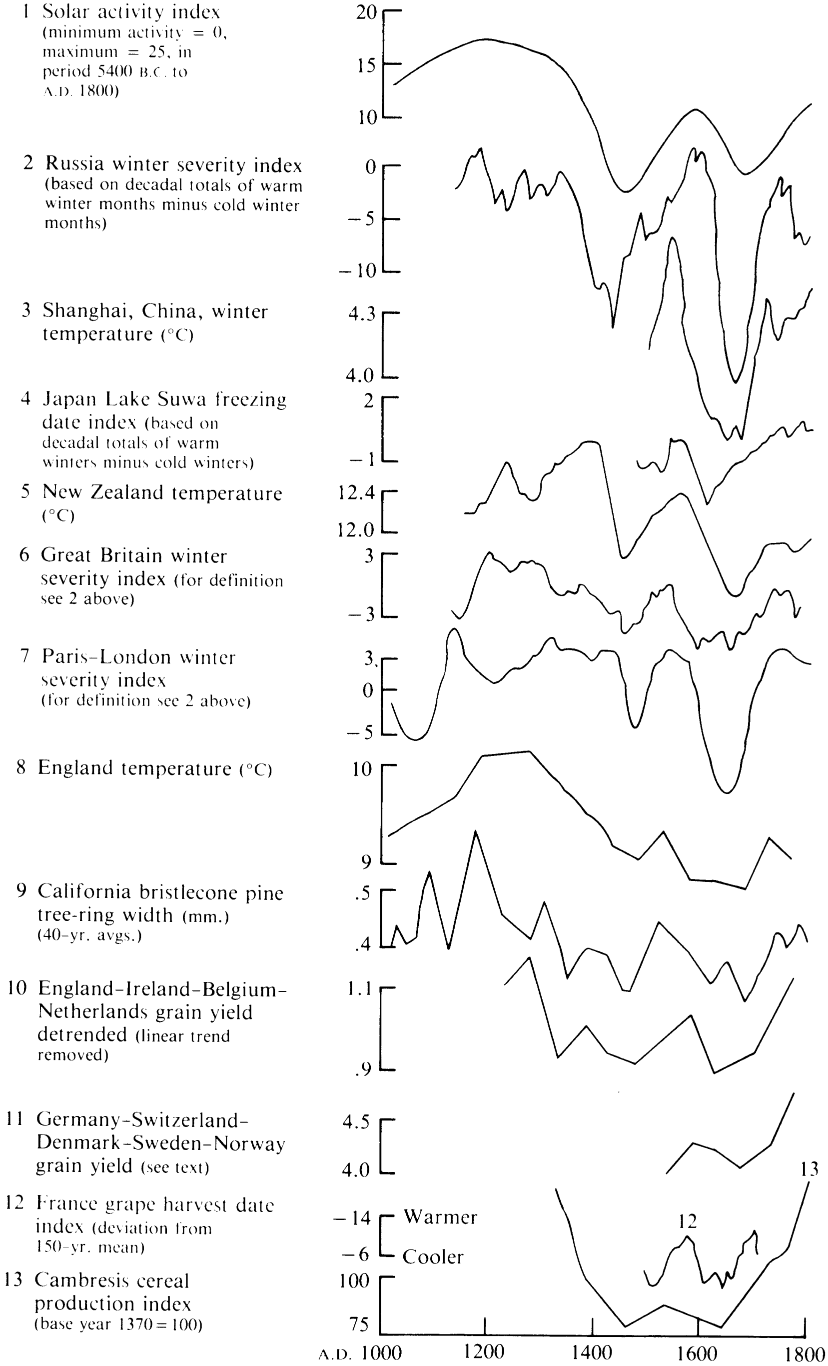
The notion of long-term fluctuations necessarily implies some underlying trend line around which the variable under consideration appears to fluctuate. The length and amplitude of the fluctuation curve are determined by the trend line. The slope (or curvature) of the trend line itself may vary, depending on the length of the temporal interval under consideration. In general this temporal interval is determined by data availability. In this study, the secular trend is removed from any series having an obvious trend, to facilitate analysis and graphic comparisons with other series.

Implicit in the hypothesized model is the notion that there actually were historical long-term fluctuations in climate. Until the last few decades it was a common belief that climate was stable throughout recorded history. As Utterström observed, ''Ever since Malthus and Ricardo, all discussions of the pressure on food supplies have started from the assumption that population is the active factor and Nature the fixed'' (1955: 3). Recently it has come to light that climate is subject to significant long-term fluctuations and these fluctuations are synchronous across the middle latitudes.

The oldest series of instrument records of temperature were published by Manley (1974) for England beginning in 1659. They are of little value for purposes of measuring long-term fluctuations, since long-term climatic cycles are measured in centuries. Climatic historians have employed a number of ingenious methods to reconstruct the climate of the past over long time periods. These range from the analysis of mineral deposits in New Zealand stalagmites, to the measurement of carbon-14 concentrations in ancient trees, to the more mundane analysis of historical documents. Meteorological series for various places throughout the middle latitudes from the years 1000 to 1800 are shown in Figure 2. In most cases the data are smoothed using 50-year averages. The series cover a broad geographical area that includes Great Britain, France, Russia, China, Japan, New Zealand, and California. The most striking feature of the various series is their remarkably synchronous movements. Although the amplitudes vary, due in part to the different scales used, the turning points appear to occur at about the same time. Williams and Wigley's (1983: 298–299) review of summer temperature variations in the northern hemisphere reveals similarly synchronous movements among temperature proxies in the middle latitudes.

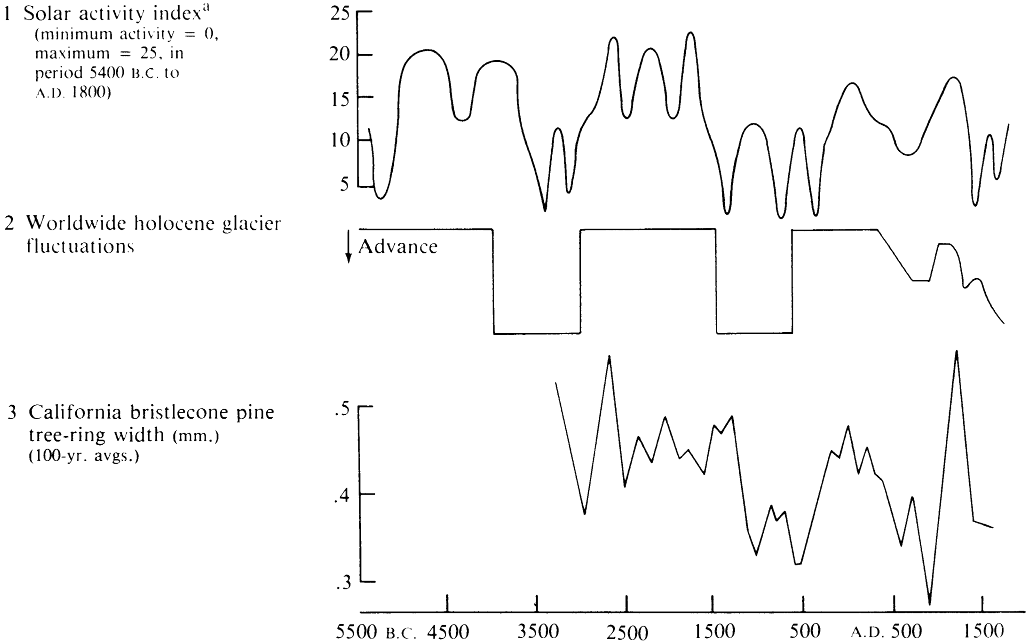
The implication of the synchronous movements of the meteorological series is that some exogenous factor is uniformly affecting middle latitude climatic change. Eddy (1977a, 1977b, 1981) and Libby (1983: 46) among others contend that these long-term climatic fluctuations are probably a consequence of long-term variations in solar activity. Eddy has constructed a record of solar activity from 5400 B.C. to A.D. 1800 based on the concentration of carbon-14 found in ancient trees (1977b: 181–182). This series, along with series of variations in worldwide glacier movements and tree-ring widths of

FIGURE 2 Meteorological and agricultural series, A.D. 1000–1800



NOTE: 50-year averages plotted every 50 years unless otherwise noted.
SOURCES: See note 1 at the end of this article.

FIGURE 3 Meteorological and tree-ring width series, 5400 B.C.–A.D. 1800



[a]See note 2.
SOURCES: See note 3.

California bristlecone pines, is shown in Figure 3. Eddy suggests that these series may represent the approximate timing of variations in middle latitude temperature (1981: 164–167).

The meteorological series shown in Figure 2 indicate that the climate of the middle latitudes over the last millennium has been punctuated by two relatively cold periods. A long warm period occurred during the late middle ages, peaking around 1200, followed by a fairly rapid cooling, reaching a minimum around the mid-fifteenth century. This was followed by a rather short warming trend that peaked around the end of the sixteenth century. A subsequent period of rapid cooling, centered around the last half of the seventeenth century, was then followed by warming. Among climatic historians the period of general cold in the fifteenth century is called the Spörer Minimum, while the cold period in the seventeenth century is known as the Maunder Minimum.

The climatic historians Bryson and Murray list the chief characteristics of climatic history gleaned from numerous studies (1977: 153–155). They are echoed by Gribbin and Lamb (1978: 31): the climate tends to change rapidly rather than gradually; climatic changes can alter the course of civilizations; synchronous changes at many points on the globe indicate that the causes must have been global; our present climate is not necessarily "normal" in the longer perspective; during cooler periods there is greater variability in week-to-week and year-to-year weather; and a cooling and variable climate brings serious problems for food production. Recent empirical work reveals a strong association between decreasing mean temperature and increasing variability in month-to-month and year-to-year temperature. Studies dealing directly with this issue include DeVries's analysis of Dutch temperature data beginning in 1634 (1981: 48), my own work on central England temperature data from 1670 to 1830 (1985: 494–495), and Fridlizius's examination of eighteenth century Swedish temperature data (1984: 94). The importance of these characteristics, especially the greater variability in weather during cooler periods, will become evident in the discussion of climate and vital rates.

Climate and food supply

Having established with some assurance the existence of long-term fluctuations in middle latitude temperatures, I now present evidence for the existence of a systematic relationship between these fluctuations and some measure of long-term variations in carrying capacity. I have chosen two measures. The first is long-term variations in agricultural yield (number of seeds yielded per seed planted). It is the less satisfactory of the two since it can be affected by human agency. The other measure is long-term variations in the growth rate of trees as reflected in tree-ring widths. It will be shown that the latter variations are independent of human activity.

Slicher van Bath notes the importance to preindustrial populations of agricultural yield: ". . . any rise or fall in agricultural production resulting from higher or lower yield ratios affected the economic life of the entire region or country . . ." (1967: 26). He continues: "Changes in the amounts harvested, the milk yield and the weight of cows and pigs are cardinal factors for determining the overall economic trend of a predominantly agricultural society. Of these trend indices, the fluctuations in the corn harvest are by far the most important" (1967: 28).

Evidence for short-term relationships between climate and food supply per capita will be evaluated first, bearing in mind that conclusions reached from short-term analysis do not necessarily apply to long-term phenomena. The relationship between yearly changes in the weather and the annual harvest is an admittedly complex issue (Slicher van Bath, 1977: 57–59). For example, a two-week period of intense rain during autumn can destroy an entire harvest. Nonetheless, evidence suggests a significant correlation between some yearly meteorological events and annual agricultural yield. Bergthorsson finds a very strong positive relationship between hay yield and winter temperature in Iceland between 1901 and 1975 (1985: 116, 123). He notes that cold winters are more effective than cold summers in restricting grass growth (1985: 113). Cold winters reduce the carrying capacity of grassland, which in turn reduces the number of livestock (1985: 117–118). Similarly Eckstein et al. find that the annual Swedish harvest index is significantly positively correlated with annual winter temperature from 1756 to 1869 (1982: 28). Eckstein et al. find no significant correlations between the Swedish harvest and spring, summer, or autumn temperatures, or annual rainfall. DeVries finds a significant negative correlation between the annual price of rye and annual winter temperature in the Netherlands during the period 1635 to 1839 (1981: 25). Over the short run, winter temperature probably has some effect on agricultural yield.

Over the long run the relationship between climatic change and crop yield may be more clearcut. The obvious impact of a long period of cooling is to lower the elevation where crops can be effectively grown, in effect decreasing the amount of land available for cultivation and leading in turn to either a decline in total output or more intense cultivation and lower yields. A cooling period would shorten the length of the growing season. Lower yields might also result from the biological inability of certain grains to effectively withstand cooler periods and their associated climatic instability. Parker and Smith suggest that a one-degree centigrade decline in temperature in Europe will lower the maximum altitude of cultivation by about 500 feet and shorten the growing season by three to four weeks (1978: 8).

In his analysis of European grain yields from 810 to 1820, Slicher van Bath divided Europe into four regions: England–Ireland–Belgium–Netherlands, France–Spain–Italy, Germany–Switzerland–Denmark–Sweden–Norway, and Czechoslovakia–Poland–Latvia–Estonia–Russia. During this epoch there are two long periods of temporary falls in average yield ratios. The two periods are 1300 to 1499 (with a very slight upturn from 1350 to 1399) and 1600 to 1699. "During these periods the falls are found in practically all cereals and in all four groups of countries, at least so far as statistics are available to prove this" (1967: 56). Both periods correspond very well to periods of middle latitude temperature decline.

The bottom portion of Figure 2 presents agricultural series from a variety of sources: the California bristlecone pine tree-ring widths, European grain yields, the dates of the French grape harvest, and estimates of cereal production based on tithes in Cambresis. The England–Ireland–Belgium–Netherlands grain yield is presented with its trend line removed. The trend line in this case is linearly upward and may represent improvements in agricultural technology. The various agricultural series appear to fluctuate in synchrony not only among themselves but along with the meteorological series.

One of the most interesting series is the bristlecone pine tree-ring widths shown in Figures 2 and 3. While it is possible that the agricultural yields in Europe may have suffered more as a result of the expansion of cultivated fields into marginal areas (due to population increase) than as a result of climatic deterioration, no such argument can be made for the bristlecone pine trees. These trees, located at the upper treeline in the White Mountains of southern California, probably represent one of the few instances of terrestrial data that are not likely to have been contaminated by human agency. "At these sites tree growth is limited by temperature with low growth reflecting low temperature" (National Research Council, 1980: 152). The long-term fluctuations in the widths of bristlecone pine tree rings are almost certainly a result of long-term climatic variations. Recent work by Sonett and Suess (1984: 141–143) provides convincing support for this idea. That these fluctuations are in synchrony with the other meteorological and agricultural series further supports the link between climatic changes and agricultural variation over the long term.

Climate and vital rates

Climatic change can affect vital rates in two ways: through its influence on food supply per capita and through direct biometeorological effects of deteriorating climate. The only previous empirical research on these subjects has been limited to analyses of short-run effects. It is of course speculative to apply short-run results to long-term analyses, but such results are not totally irrelevant. Short-term (year-to-year) analysis does have the virtue of eliminating the feedback link from population to food supply, discussed earlier, since annual variations in the harvest—the main determinant of food supply—are primarily caused by the complex interaction of various climatic factors.

Mortality will be considered first. It has been shown that long-term fluctuations in climate are associated with long-term fluctuations in agricultural yield. A period of cooling, with its attendant decrease in agricultural yield and increase in the frequency of famines, can lead to elevated mortality in a number of ways. The most obvious is through outright starvation, although the most likely is through the body's increased susceptibility to infectious diseases as a result of its weakened nutritional state. It is also likely that heightened migration, especially rural to urban, during times of increasing famines will tend to raise the overall probability of interaction among different members of the population, which in turn will lead to an increase in the incidence of infectious diseases, and of course to an increase in mortality. Recent research on the annual responses of vital rates to annual fluctuations in the harvest in the preindustrial era shows a significant positive correlation between increasing grain prices and increasing mortality in England (Lee, 1981: 375), London (Galloway, 1985: 496), Sweden (Bengtsson and Ohlsson, 1984: 343, 353), southern Sweden (Bengtsson, 1984: 343), and France (Richards, 1983: 206; Weir, 1984: 45, 47). These results are corroborated by the decline in mortality associated with abundant harvests found in Sweden (Eckstein et al., 1982: 28) and Croatia (Hammel, 1985: 286).

Turning to the direct effects of temperature on mortality, recall that Bryson and Murray found one of the main characteristics of periods of climatic cooling to be an increase in the week-to-week and month-to-month variability of the weather. Tromp, in his exhaustive examination of the biometeorological literature, finds that one of the key meteorological factors associated with increasing mortality is increasing variability in the weather (1980: 149–150, 159, 174, 225–226). Howe (1972: 18–19) and Bull and Morton (1975: 232) provide corroborating support. It is likely that a direct result of the heightened variability in the weather associated with a period of long-term cold is an increase in mortality. Looking again at short-run empirical results, Eckstein et al. (1982: 28) find in Sweden, Lee finds in England (1981: 393), and I found in London (1985: 496) that a decrease in winter temperature is significantly correlated with an increase in mortality independent of the harvest. Eckstein et al. find little impact of cool summers on mortality in Sweden; however, Lee finds in England and I found in London that cooler summers tend to reduce mortality.

The effect of long-term fluctuations in climate on fertility is more complex. The associated decrease in agricultural yields, along with an increase in the frequency of famines, probably leads to a general decline in nutrition. This may result in a later age at menarche, higher frequency of sterility, an increase in spontaneous abortions, a decline in libido, an increase in amenorrhea due to both malnutrition and psychological stress, and an increase in abstinence, induced abortion, and perhaps voluntary birth control through greater use of contraception. The data are not sufficient to measure the impact of these various factors on overall fertility, but it is evident that during periods of famine a substantial proportion of women become amenorrheic (Bongaarts and Potter, 1983: 17). In addition to these direct effects, fertility would likely be reduced as a result of a decline in nuptiality. The ability of a prospective couple to establish a household should be constrained as agricultural productivity declines. We must once again rely for empirical support on analyses over the short run. Fertility is significantly negatively correlated with grain prices in preindustrial England (Lee, 1981: 375), southern Sweden (Bengtsson, 1984: 354), and France (Richards, 1983: 205; Weir, 1984: 45, 47). A rise in fertility is associated with an increase in the harvest in Sweden (Eckstein et al., 1982: 28) and Croatia (Hammel, 1985: 286).

Variations in temperature associated with long periods of cold may also affect fertility. The neuroendocrine mechanism involved is described by MacFarlane (1977: 573–577). The neuroendocrine activity that governs fecundity in the female is reduced when temperatures are above or below some optimal level. Clearly, female fecundity should decline during periods of increasing climatic variability. Turning once again to short-term evidence, Eckstein et al. find that colder-than-average winters are associated with a decline in fertility independent of grain prices in Sweden (1982: 46). Lee finds that cooler winters and warmer summers reduce fertility in England (1981: 397).

Regarding internal migration, one might expect that a long-term decrease in agricultural yields and a corresponding increase in the frequency of famines as a result of a cooling climate would lead to a long-term increase in human and animal migration in search of food. This would elevate mortality by increasing the frequency of interaction among different groups of the population, which in turn would increase the frequency of epidemics and the probability of contracting infectious diseases.

A cold period and its associated deterioration in agricultural yields would have its greatest effects in marginal areas, particularly those at higher elevations. It is likely that these areas would experience significant outmigration and in some cases abandonment.

Long-term fluctuations in climate and population in preindustrial England

The hypothesized links of temperature and agricultural yield to vital rates are generally supported by short-term analysis. However, one must look to long-run analysis for more convincing evidence. Series of vital rates covering many centuries are needed to convincingly test the proposed model. Although such data are not available, a series of vital rates for England beginning around the middle of the sixteenth century is presented in Figure 4, along with series of temperatures and agricultural yield. Examination of any of the series in Figure 4 reveals only one cycle between 1550 and 1800—that is, two troughs or two peaks. Nonetheless the turning points, few as they are, support the proposed model. During the cooling period from around 1590 to 1670, grain yield, measures of fertility, and life expectancy are low, and the population growth rate declines. The average age at first marriage and net outmigration rise. During the period of warming from around 1670 to 1800, grain yields increase, along with measures of fertility and life expectancy at birth (though only slightly), leading to an upswing in the population growth rate. The average age at first marriage and the net outmigration rate decline. In this case the long-term fluctuations in vital rates take the shape of nearly sinusoidal curves; hence detrended population follows the population growth rate by about one-quarter cycle (see Lee, 1985).

Meteorological and population series in Europe, China, and North America

While there is little information on long-term movements in vital rates, various population estimates have been made for a number of countries. By simply plotting the logarithm of population and the logarithm of a proxy for middle latitude temperature—for instance, solar activity—one can obtain a rough picture of the relationship between the two variables. This relationship is shown in Figure 5 for a number of European countries and China from 1250 to 1800. The generally synchronous movement of population among all the areas is noteworthy. The series have been divided into approximate periods of warming and cooling. In general, population grows during warming periods; in cooling periods it stagnates or declines, as hypothesized.

Crude estimates of population have been made for a number of areas covering the period 400 B.C. to A.D. 1800. These are presented in Figure 6, along with two proxies for climatic change: solar activity and the California bristlecone pine tree-ring widths. While the population estimates are admittedly rough, they are in close agreement with most scholarly opinion (Clark, 1968; Durand, 1974). There appears to be a striking similarity in the population growth patterns of China and western Europe. McEvedy and Jones note that "events at opposite ends of the Eurasian land mass have an astonishing synchronicity" (1978: 345). Further examination of Figure 6 shows the synchronous movement of the Chinese and European populations with solar activity and bristlecone pine tree-ring widths. In warming periods, population grows; in cooling periods, it stagnates or declines.

It is likely that marginal areas would be most affected by deteriorating climate. Evidence for this is taken from archaeological finds on Roten Moor in Germany, in the small village of Hoset in Norway, in Hay Hollow Valley on a high plateau in Colorado, and on upland farms in Scotland. Estimated population or habitation series are shown in Figure 6.

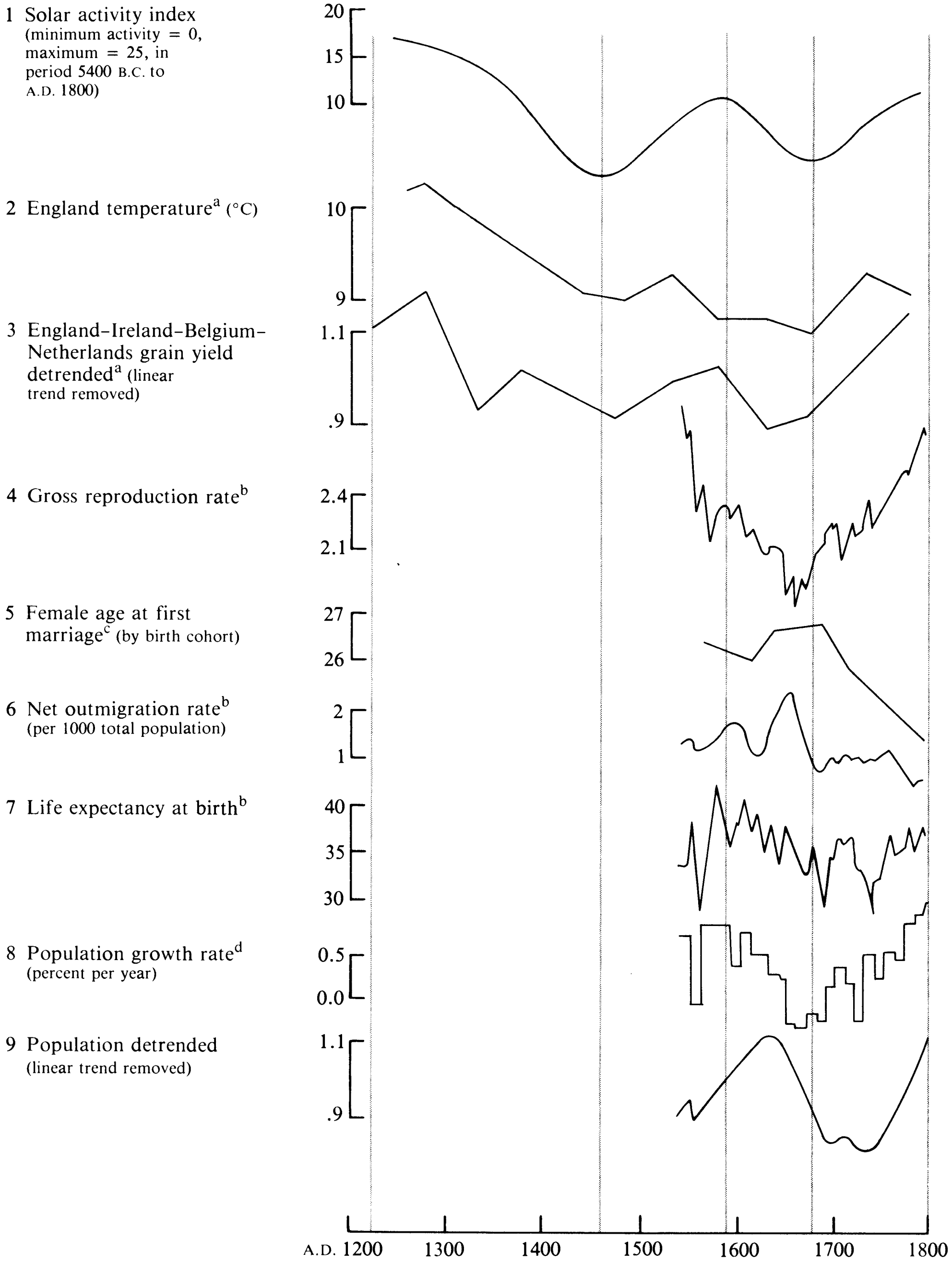
Roten Moor was noted for being one of the more isolated and desolate areas of central Germany. Pollen analysis at the site reveals an interesting story. The concentration of grain pollen relative to other types of pollen is considered to be fairly reliable evidence for human occupation and, of course, grain cultivation. It appears that the moor was first cultivated during Roman times and grew to a peak population around 1200, followed by a precipitous decline leading to near abandonment in the fourteenth and fifteenth centuries. The site was occupied again during the warm period of the sixteenth century, only to be nearly abandoned once more during the cold seventeenth century (Abel, 1955: 47). The fluctuations of Roten Moor cultivation correspond extraordinarily well to long-term climatic fluctuations.

The Hoset settlement has been the object of detailed investigation by researchers at the University of Trondheim in Norway. By piecing together literary evidence in combination with pollen analysis and archaeological evidence, a reasonable account of its settlement pattern has emerged. Cultivation was introduced some time in the sixth or seventh century, and the settlement grew to a peak around 1170. The site had been virtually deserted by 1435, only to be resettled again between 1550 and 1690. Literary evidence indicates that the site was again abandoned in 1698 and was never fully cultivated thereafter until the 1930s (Salvesen et al., 1977: 140–150). As with Roten Moor the peaks and troughs of population settlement correspond precisely with peaks and troughs of the climatic series.

Hay Hollow Valley is located on the Black Mesa plateau in Colorado. The site, first inhabited around A.D. 200, reached a maximum population around 1200 and was permanently abandoned during the cold period of the fourteenth and fifteenth centuries (Euler et al., 1979: 1094). The periods of settlement and abandonment correspond to periods of climatic warming and cooling.

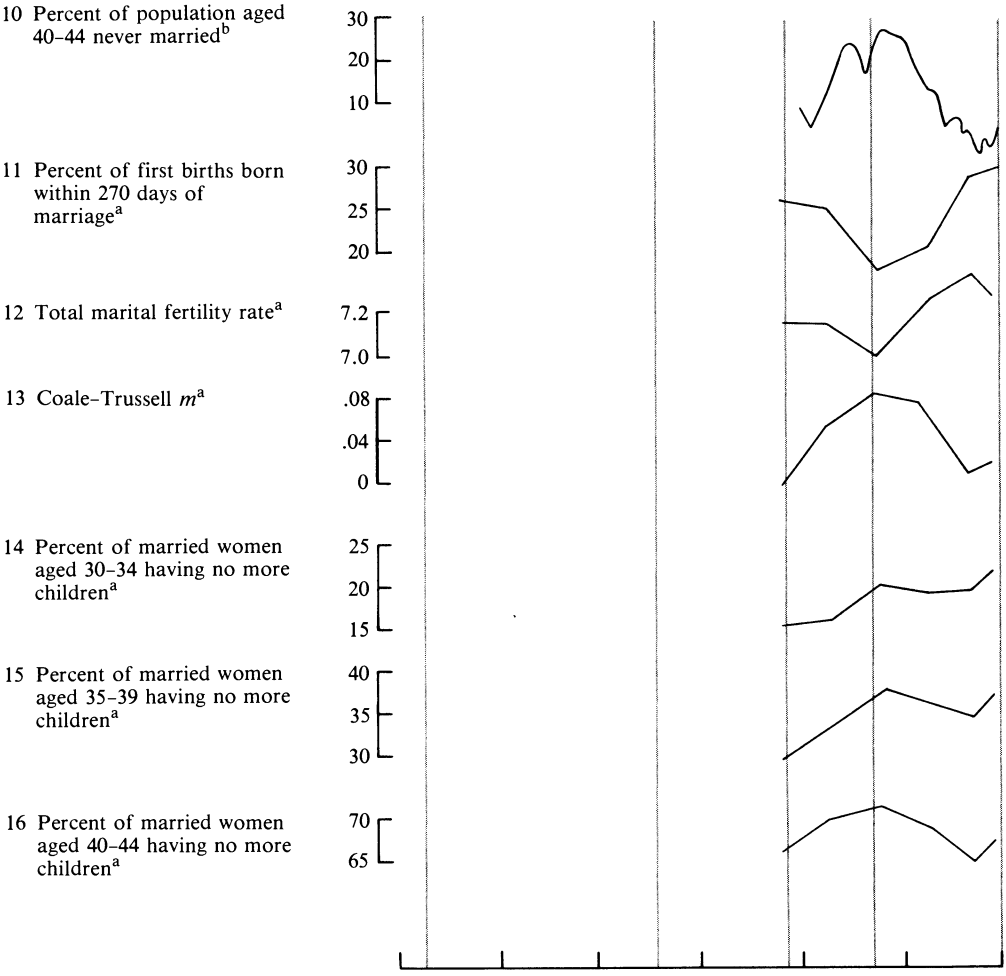
Parry (1981: 319–336) has traced farmland abandonment in upland Scotland. Cultivation peaks around 1200, reaches a trough around 1400, rises again until around 1500, then declines dramatically until around 1650, after which it begins to rise again. These peaks and troughs are synchronous with middle

FIGURE 4 Meteorological, agricultural, vital rates, and population series for England, A.D. 1250–1800



latitude climatic warming and cooling. Parry notes that "while political upheaval, the Black Death, the decline of the monasteries, or even runs of

FIGURE 4 (continued)

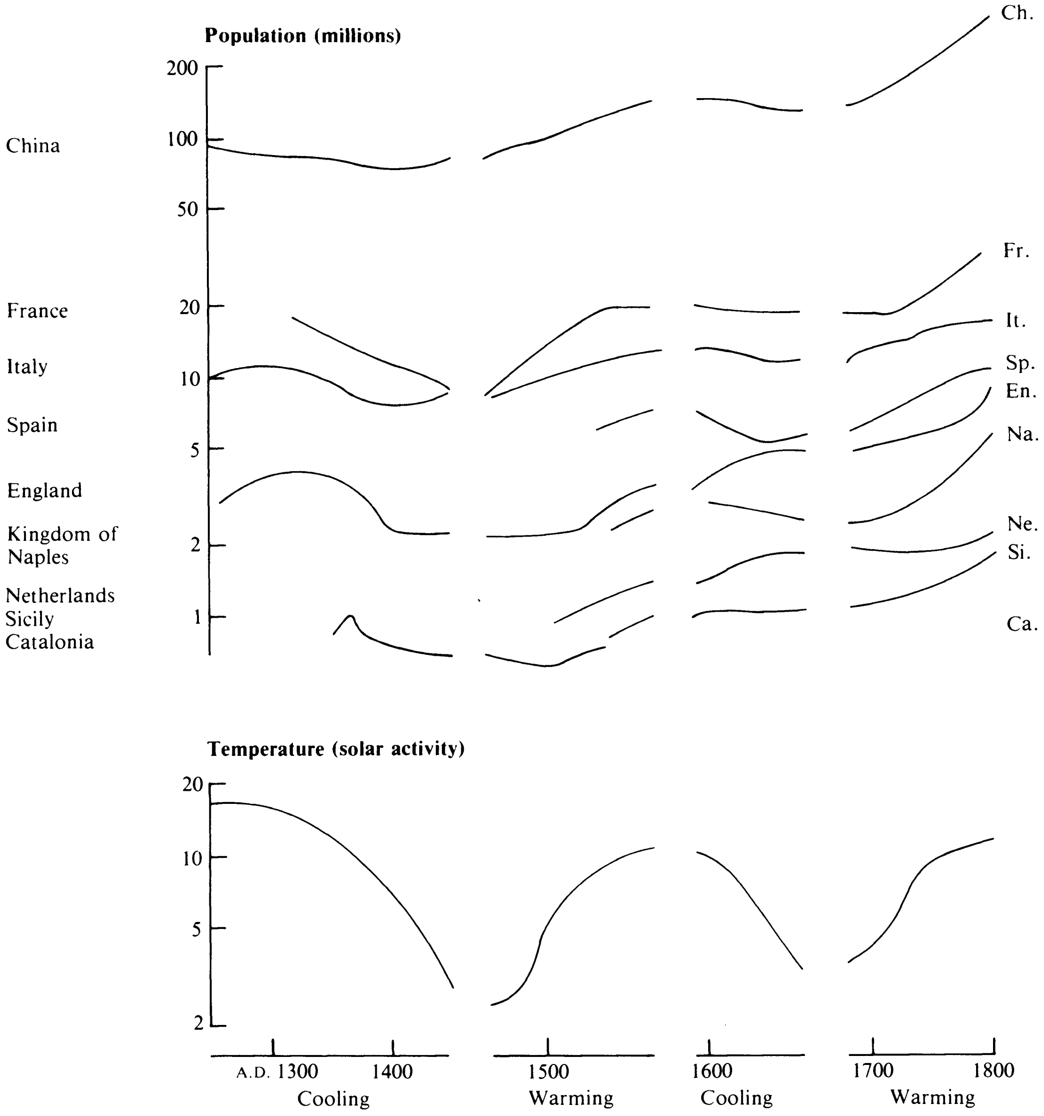


NOTE: Data from Wilson, 1982, are for 16 parishes.
[a]50-year averages plotted every 50 years. [b]5-year averages plotted every 5 years.
[c]25-year averages plotted every 25 years. [d]10-year intervals.
SOURCES: See note 4.

disastrously poor summers in the 1590's and 1690's, may have triggered the retreat of high-level cultivation, it was the operation of these forces on a marginality enhanced by climatic deterioration in the fourteenth and seventeenth centuries that produced such a marked and lasting effect'' (1981: 331–332).

The relative sensitivity of different populations to long-term fluctuations in climate can be estimated using regression analysis. Ideally one would like to regress vital rates on temperature over a couple of millennia. Although data

FIGURE 5 Meteorological and population series in European areas and in China, A.D. 1250–1800 (log scales)

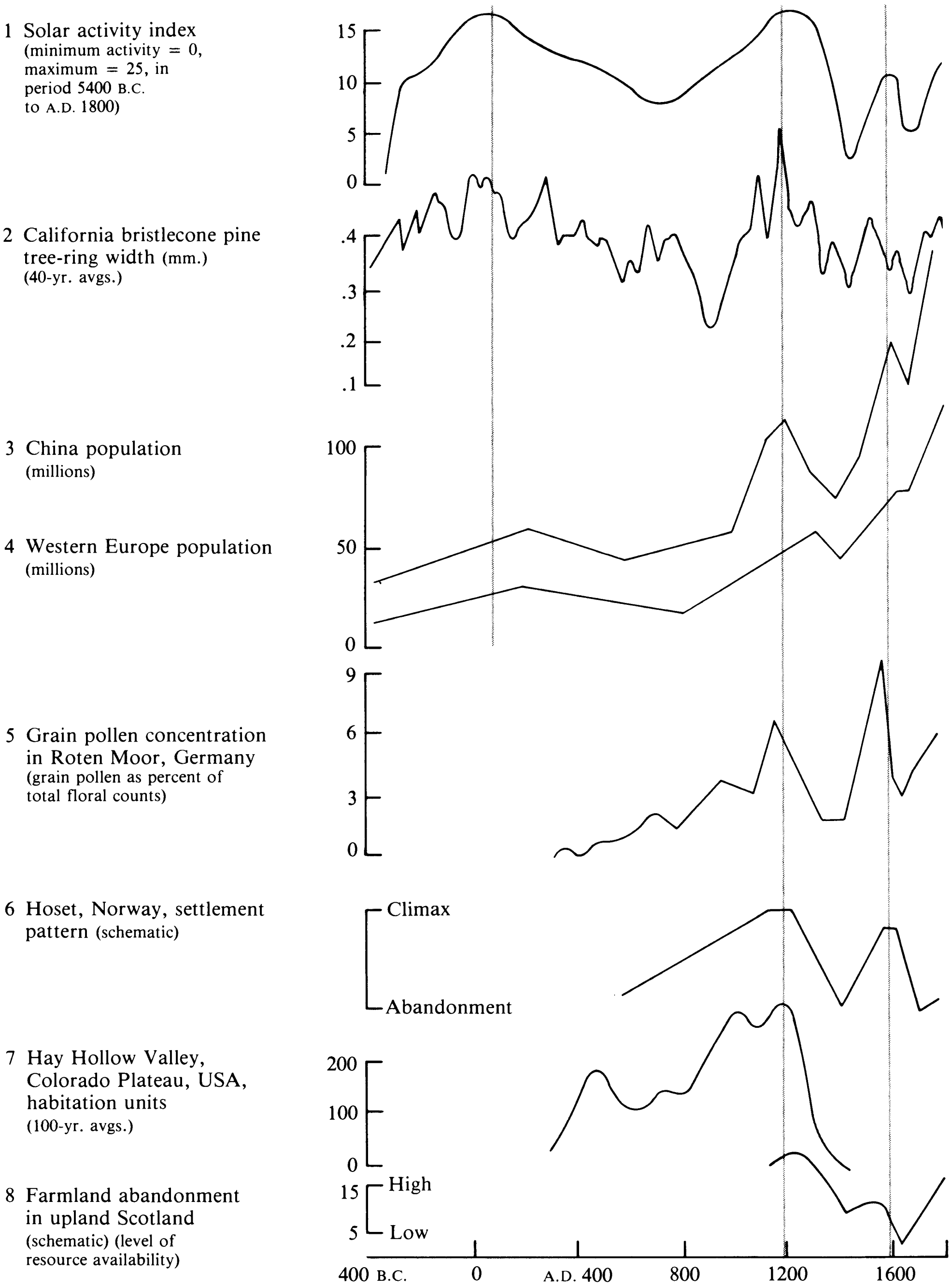


SOURCES: See note 5.

for such analysis are nonexistent, crude estimates of middle latitude population and rough proxy measures of temperature are available back to 400 B.C.

Regressions are run first for the populations of China and western Europe from 400 B.C. to A.D. 1800 and then for the populations of China and western Europe and for grain pollen concentration (a proxy for population) on Roten

FIGURE 6 Meteorological and population series for China, western Europe, and settlements in Germany, Norway, Colorado, and Scotland, 400 B.C.–A.D. 1800



SOURCES: See note 6.

Moor from A.D. 450 to 1800. The independent variables are time and solar activity (a proxy for temperature). Time (t) presumably represents technology and/or capital accumulation. An attempt is made to eliminate the trend from the population and grain pollen variables, using parabolic (t and t^2), squared (t^2), and cubic (t^3) terms. Data are taken at 50-year intervals. The regressions are corrected for second-order autoregressive disturbances using the Cochrane–Orcutt iterative procedure.* The results are presented in Table 1. Solar activity, a proxy for temperature, is positive and highly significant in all regressions. The various detrending procedures do not affect the significance of solar activity.

Equations 1 to 6 cover the time period 400 B.C. to A.D. 1800 for China and western Europe. By examining the elasticities shown in Table 1, one can obtain a clearer picture of the relative responses of Chinese and western European populations to the climate (solar activity). A 10 percent increase in solar activity produces on average a 3 percent increase in population in China and about a 4 percent increase in western Europe.

If the range is restricted to A.D. 450 to 1800, as in equations 7 to 15, a similar picture is revealed. Both China's and western Europe's responses to a 10 percent increase in solar activity are a growth in population of about 4 percent. The elasticity of Roten Moor, a marginal area, over the same time period is about 7 percent. This is consistent with the notion that population levels in a marginal area should be more sensitive to climatic change.

Discussion

There are a number of critics of the climatic theory of population growth. Le Roy Ladurie has dismissed the idea for lack of sufficient quantitative evidence (1971). Since that time, both climatic historians and demographic historians have provided us with information to reconstruct past climates and populations of a number of places around the world.

More recently Anderson, while admitting that the economic depressions of the fifteenth and seventeenth centuries coincided with periods of unfavorable climate, attributed these downturns to social and economic forces (1981: 337). It is possible, however, that the social and economic forces in question are themselves triggered by climatic changes, especially in light of the impact climate may have had on carrying capacity and vital rates.

It has been suggested that the decline in European population between 1348 and the late fifteenth century was due to continual outbreaks of bubonic

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* The Cochrane–Orcutt iterative procedure is a differencing technique used to correct for serial correlation. A correction for second-order autoregressive disturbances is applied using the Cochrane–Orcutt iterative procedure, where the error process is defined as $e_\tau = s_1 e_{\tau-1} + s_2 e_{\tau-2} + u_\tau$ where τ is time, e is the error term, u is an independently distributed random variable, and s is a coefficient. In a series with a moderate to large number of observations this correction should have little effect on the value of the regression coefficients, but should provide a better estimate of their significance (Harvey, 1981: 189–199).

TABLE 1 Regressions of the populations of China and western Europe and Roten Moor grain pollen concentration on time and solar activity from 400 B.C. to A.D. 1800 and from A.D. 450 to A.D. 1800

400 B.C. to A.D. 1800

			Independent variable						
Eq.	Dependent variable	Constant	t	t^2	t^3	Solar activity	Elasticity*	n	R^2
1	China	87.76	− 15.08 c	.48 b		1.84 a	.27	45	.78
2	China	−2645.20		2.56 b		1.99 a	.30	45	.67
3	China	−27.34			.0043 a	1.95 a	.29	45	.77
4	W. Europe	16.22	−3.16 a	.11 a		1.42 a	.44	45	.89
5	W. Europe	−7.12		.06 a		1.21 a	.37	45	.75
6	W. Europe	−3.25			.0013 a	1.29 a	.40	45	.87

A.D. 450 to A.D. 1800

			Independent variable						
Eq.	Dependent variable	Constant	t	t^2	t^3	Solar activity	Elasticity*	n	R^2
7	China	721.01	−54.76 a	1.02 a		3.33 a	.38	28	.86
8	China	−250.22		.35 a		3.33 a	.38	28	.70
9	China	−119.86			.0058 a	3.30 a	.38	28	.77
10	W. Europe	124.07	−10.29 a	.21 a		1.68 a	.41	28	.97
11	W. Europe	−30.19		.06 a		1.73 a	.42	28	.87
12	W. Europe	−15.51			.0013 a	1.73 a	.42	28	.93
13	Roten Moor	−4.49	.19	−.0003		.19 b	.63	28	.53
14	Roten Moor	−1.96		.0028 a		.22 a	.71	28	.55
15	Roten Moor	−1.32			.00006 a	.23 a	.78	28	.54

NOTES: The regressions are corrected for second-order autoregressive disturbances using the Cochrane–Orcutt iterative procedure (see footnote on p. 18).

* Elasticity can be interpreted as the percentage population response to a one percent increase in solar activity.

t = time.

n = number of observations.

R^2 = corrected R^2 calculated for the untransformed variables.

The t statistic significance levels are indicated as follows: a = 1 percent, b = 5 percent, c = 10 percent.

SOURCES: Dependent variables: China population is from McEvedy and Jones, 1978, p. 171.
Western Europe population is from McEvedy and Jones, 1978, p. 28.
Roten Moor grain pollen concentration is from Abel, 1955, p. 47.
Independent variable: Solar activity is from Eddy, 1977b, pp. 181–182.

plague. Some one-fourth to one-third of the European population died during the early years of the outbreak. It is known that the plague was spread by flea-infested rats in close contact with humans. Utterström argues that an increase in rat migration may have been associated with declining food supplies over the long term, a decline that may have been due to climatic deterioration (1955: 34). The period from 1348 to around the mid-fifteenth century was one of climatic cooling. It is also noteworthy that the great outbreaks of plague in the sixth century and in the mid-seventeenth century occurred during temperature minimums.

Figure 6 shows that a period of widespread cooling began around 1200, leading one to expect that population levels in Europe would have begun to decline before 1348 according to the proposed climatic model. Del Panta shows population in Italy beginning to decline around 1300 (1980: 102–110, 135), while Pounds notes that in Europe in general ". . . the population had fallen somewhat in some areas quite early in the [fourteenth] century, if not in the later years of the thirteenth. . . . Meteorological conditions may have been related to a cyclical deterioration of climate, which had begun in the previous [thirteenth] century. The climate did not itself cause the epidemics; it merely provided the conditions in which infections could spread" (1973: 325). Postan suggests that in England ". . . the true turning point [in population] must have occurred at least two decades before the outbreak of the pestilence, or perhaps even earlier. The outbreak [of plague in 1348] must greatly have aggravated the slump in population, even if the latter had been triggered off by other factors. But however aggravated, the slump may well have begun much earlier, and, if so, was due to causes other than the Black Death or the Black Death alone" (1978: 42). Hodgett notes that in medieval Europe "there is good evidence for thinking that the population explosion which probably started in the eleventh century was dying down before the arrival of the plague" (1974: 201). He suggests that one ". . . cause of the down-turn in some parts of Europe may have been the worsening climate of the fourteenth century, which had a deleterious effect upon harvests and which completely prevented the cultivation of some crops" (1974: 202).

The increased variability in the weather associated with periods of cold has been emphasized throughout this analysis. Indeed, ". . . changes in variability are at least as important in determining the impact of climate on Man as changes in the mean" (Ingram et al., 1981: 17). Rabb suggests that "in general, it is stability, and thus predictability, that allows effective societies to develop and take root. The single worst consequence of a climatic regime is a demand for constant change and adaptation. At such times, the negative impact on human history, forcing withdrawals from settlements, trade routes, and occupations, has been unmistakable. . ." (1983: 637).

Finally, it should be clear that Malthusian theory is not an essential component of the climate–population model (recall the discussion of the population–food supply per capita feedback loop shown in Figure 1). One of the primary problems with Malthusian theory is that it is difficult to support empirically over the long term since its two components, population growth and food supply per capita, feed back on each other, making causal inferences troublesome. Furthermore, Malthusian theory cannot account for the timing of observed long-term fluctuations in population. The proposed climate–population model, on the other hand, effectively predicts the turning points observed in preindustrial populations.

Any conclusions emerging from the study of long-term phenomena for which data are limited and fluctuations few must be viewed as somewhat speculative. The primary empirical support for the proposed theory lies in the striking synchrony in the long-term movements of temperature, agricultural yield, and population series across space (the middle latitudes) and time (before A.D. 1800). The results of this analysis suggest that an important driving force behind long-term fluctuations in population may be long-term variations in climate and their effects on carrying capacity and vital rates.

Notes

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1 Sources for numbered series: 1. Eddy, 1977b, p. 182. 2. Lamb, 1972, pp. 219–221. 3. Lamb, 1982, p. 228. 4. Takahashi and Nemoto, 1978, pp. 184–185. 5. Wilson, 1981, p. 221. 6. Lamb, 1972, pp. 219–221. 7. National Research Council, 1980, p. 152. 8. Lamb, 1965, p. 24. 9. LaMarche, 1974, p. 1045. 10–11. Slicher van Bath, 1967, p. 94. 12. Bell, 1981, p. 273. 13. Le Roy Ladurie and Goy, 1982, p. 81.

2 The following table (from Eddy, 1977b, p. 181) lists major fluctuations in solar activity over the past 7400 years. It is consistent with the solar activity series shown in Figure 3.

Major solar excursion	**Probable extent in real time**
Modern Maximum	A.D. 1780? –
Maunder Minimum	A.D. 1640–A.D. 1710
Spörer Minimum	A.D. 1400–A.D. 1510
Medieval Maximum	A.D. 1120–A.D. 1280
Medieval Minimum	A.D. 640–A.D. 710
Roman Maximum	20 B.C.–A.D. 80
Minimum	440 B.C.–360 B.C.
Minimum	820 B.C.–640 B.C.
Minimum	1420 B.C.–1260 B.C.
Maximum	1870 B.C.–1760 B.C.
Maximum	2370 B.C.–2060 B.C.
Maximum	2720 B.C.–2610 B.C.
Minimum	3220 B.C.–3110 B.C.
Minimum	3430 B.C.–3330 B.C.
Minimum	3690 B.C.–3470 B.C.
Maximum	4240 B.C.–3760 B.C.
Maximum	5070 B.C.–4510 B.C.
Minimum	5320 B.C.–5110 B.C.

3 Sources for numbered series: 1. Eddy, 1977b, p. 182. 2. Denton and Karlan, 1973, p. 158. 3. LaMarche, 1974, p. 1046.

4 Sources for numbered series: 1. Eddy, 1977b, p. 182. 2. Lamb, 1965, p. 24. 3. Slicher van Bath, 1967, p. 94. 4–10. Wrigley and Schofield, 1981, various pages as follows: 4. p. 230. 5. p. 424. 6. pp. 531–545. 7. p. 230. 8–9. pp. 531–535. 10. p. 260. 11–16. Wilson, 1982, various tables as follows: 11. Table 2.2. 12. Table 2.1. 13. Table 4.1. 14–16. Table 6.1.

5 Sources for population series: China: McEvedy and Jones, 1978, p. 171. France: Le Roy Ladurie, 1975, pp. 576–577. Italy: Del Panta, 1980, p. 135. Spain: Mauro and Parker, 1977, p. 37. England: Wrigley, 1969, p. 78; Coleman, 1977, p. 12; Wrigley and Schofield, 1981, pp. 531–535. Kingdom of Naples: Felloni, 1977, pp. 2–3. Netherlands: DeVries, 1982, Table 1. Sicily: Felloni, 1977, pp. 2–3. Catalonia: Miskimin, 1969, p. 28. Source for temperature (solar activity) series: Eddy, 1977b, p. 182.

6 Sources for numbered series: 1. Eddy, 1977b, p. 182. 2. LaMarche in Lamb, 1982, p. 133. 3. McEvedy and Jones, 1978, p. 171. 4. McEvedy and Jones, 1978, p. 28. 5. Abel, 1955, p. 47. 6. Salvesen et al., 1977, pp. 140–150. 7. Euler et al., 1979, p. 1094. 8. Parry, 1981, p. 331.

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