RESEARCH IN PROGRESS

CHARACTERISTICS OF POPULATION CYCLES IN PRE-INDUSTRIAL ENGLAND

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Susan Scott obtained her Ph.D. from Liverpool University and her thesis was concerned with the demographic history of the parish of Penrith, Cumbria, 1557–1812. C.J. Duncan holds the Chair of Zoology at Liverpool University and their joint interests include population modelling, mortality crises in North West England and the historical epidemiology of infectious diseases.

Aggregative analysis of parish register series reveals that many communities and populations experienced regular cycles (or oscillations) of baptisms and burials, suggesting that the underlying population numbers were fluctuating. These regular cycles in vital events can be extracted from the annual totals by the statistical technique of time-series analysis and demographers recognize two distinct types of oscillations: exogenous and endogenous. Exogenous cycles are driven by external events, such as weather conditions or grain prices, whereas, although endogenous cycles are apparently triggered by a single external event (usually a mortality crisis), they are perpetuated and their characteristics are determined by the underlying dynamics of the population. Time-series analysis of baptismal and burial records of English parishes suggests that both the exogenous and endogenous cycles have common characteristics; in particular their periodicity (or wavelength of the cycles) seems to be remarkably standardized. Their regularity provides us with important clues concerning the underlying population dynamics.

Cycles in human populations

It has frequently been observed that human populations often appear to fluctuate in cycles. Oscillations with a periodicity of 15 years have been imposed on demographic rates, it is suggested, by the climate or by fluctuations in the quality of the harvest, and a 20-year Kuznets cycle has been found which may reflect economic-demographic interactions.[1] Longer wavelength oscillations have been detected in population size, fertility and real wages[2] in different historical periods; a 30-year cycle is found in the plotted data of baptisms from preindustrial parishes;[3] other cycles have a periodicity of one generation, but longer cycles of 40 to 60 years that are closer to two generations have also been described and the 50-year Kondratieff cycle runs through the demographic variables of nineteenth century Europe.[4] A 43-year cycle has been found in deaths in the city of Florence from 1275–1500[5] and a 55-year oscillation in the birth series of nineteenth century France.[6]

Two types of cycles have been identified. Firstly, transient, or generation-long, oscillations which reflect the intrinsic dynamics of population renewal can occur in populations growing without effective constraint, such as might occur temporarily in newly-settled areas; these oscillations diminish (or decay) over time.[7] Secondly, control (or limit) cycles which differ from generation-long cycles in that they have no tendency to decay,[8] and demographers such as Malthus and Easterlin have suggested theories for the existence of steady-state populations in which oscillations are controlled by density-dependent constraints (i.e. the balance between resources and population numbers).[9] Although the factors causing these cycles are unclear, changes in fertility and birth rate within a controlled system have been advanced as the most probable underlying control mechanism; these cycles can continue unabated as long as the density-dependent check is dominant.[10] The baby boom and bust pattern in the fertility of the USA in the twentieth century is an example; the series has a periodicity of about 44 years and displays a trough in the mid-thirties, a rise to a peak in the late fifties and a further decline thereafter.[11] Other examples of human populations that have been maintained at a constant level (i.e. in steady-state) by density-dependent checks include the long-run stability of hunter-gatherer populations, recovery from demographic crises and the association of fertility with size of land holding.[12]

It is difficult to present a synthesis of these studies because they include both exogenous and endogenous cycles, they are largely concerned with the populations of whole countries rather than with single communities, little is known of the underlying population dynamics and it is not clear what initiated the oscillations.

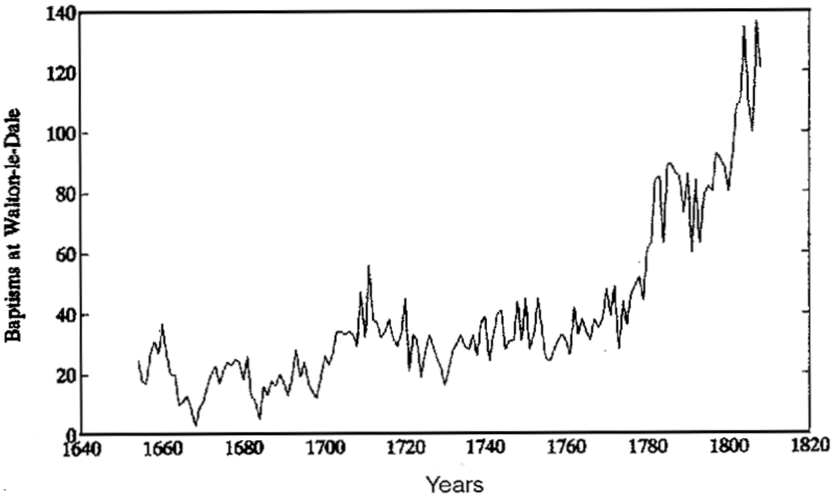
Demographic feedback models have been used to reproduce the regularity of these cycles[13] but the models were all deficient in one way or another and either failed to generate control cycles or produced a periodicity of 90 years.[14] Questions still arise as to how far the intrinsic tendencies of the population may be affected by temporary conditions, by declining mortality or by waves of immigrants, and whether in human populations there are feedback mechanisms of sufficient sensitivity to generate self-sustaining cycles.[15]

Communities in steady-state in pre-industrial England

In many communities in England the mean annual number of baptisms and burials remained approximately constant from the middle of the sixteenth century to about the middle of the eighteenth century. In addition, the mean annual number of baptisms approximately equalled the mean number of burials and we conclude that, over some 200 years, many communities remained, on the average, in steady-state although the population fluctuated within strict limits during this time; examples of density-dependent control.

A typical, over-simplistic scenario during the seventeenth century in a density-dependent situation, particularly in communities living under marginal conditions, would be for a woman to have an average of four children, two of

Figure1 Baptism series at Walton-le-Dale, 1654–1808: ordinate annual number of baptisms



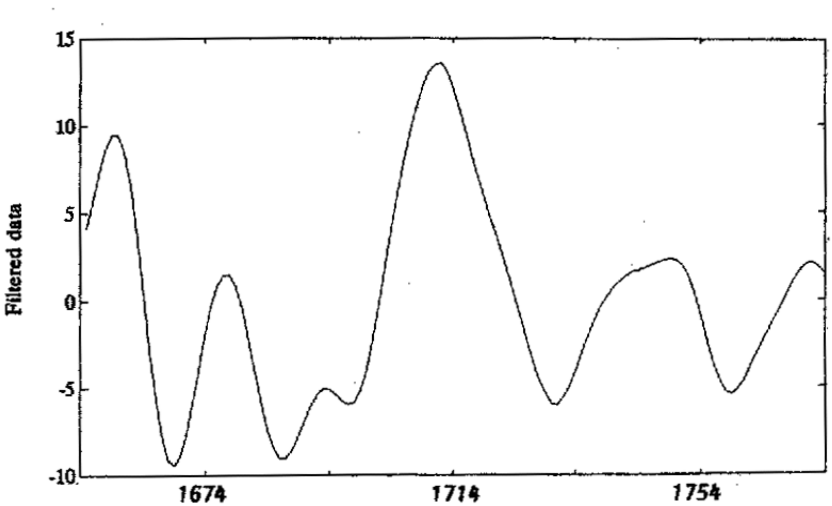
whom died before reaching reproductive age, so maintaining the *status quo.* The time taken for a women to mature and begin reproduction is very long and this fact when combined with the average production of two viable children per woman means that the population will be susceptible to mortality crises when it will produce cycles (i.e. it will oscillate).

The behaviour of these endogenous cycles is predictable from theory. One such prediction is that a cycle in the annual *baptisms* would be generated under these conditions; this endogenous cycle would have a fixed periodicity (wavelength) but would progressively fall in size (i.e. it would decay). The prediction is that the period (expressed in years) would be equal to the average age of the women in the population when they bore their middle (median) child.

Actual 30-year oscillations

Unfortunately, these decaying oscillations in baptisms are not readily detectable in a parish register series because they are frequently obscured by exogenous and other endogenous cycles. We have shown how, by using time series analysis of the parish registers, it is possible to extract and display this decaying endogenous oscillation in baptisms at Penrith, Cumbria during the period 1600–1750 when this community was in density-dependent steady-state.[16] It suffered from a severe mortality crisis when it was hit by the plague in 1598/9 which appears to have initiated the endogenous oscillation. Its wavelength was 30 years, suggesting that this was the age, on average, when the women of Penrith were at the centre of

Figure 2 Baptism series at Walton-le-Dale, 1654–1774, filtered.



Note: Filtered to remove cycles of wavelength below 20 and above 50 years. The significant 30 year cycle revealed by time-series analysis is shown.

their reproductive span and were bearing their middle child. This value has been validated by a family reconstitution study of the parish[17] and also compares well to the range of 31 to 33 years for the mean age at maternity for pre-industrial England quoted by Wrigley and Schofield.[18]

This decaying endogenous oscillation in baptisms is more readily seen at Walton-le-Dale, Lancashire. The registers begin in 1654 and continue through to 1808 and the numbers of annual baptisms are shown plotted in Figure 1; the series falls into two parts: there is only a slight rising trend before 1770 but a major increase is evident thereafter. A cycle in this baptism series during the first period is detectable by eye and time-series analysis shows that this oscillation is significant and has a periodicity of 30 years; it is revealed more clearly by the use of filtering and is shown in Figure 2. Time-series analysis of the filtered series confirms that the wavelength is 30 years. No such oscillation is detectable in the baptism series after 1770.

Although the registers at Walton-le-Dale begin only at the end of 1653, some burial entries are available from 1609 to 1641 in the Episcopal Transcripts at Chester and these show that mortality rose three-fold in 1623, a value that is comparable to other Lancashire parishes in the mortality crisis of that year.[19] We suggest that this crisis acted as a perturbation for the population which triggered the decaying cycle in baptisms which persisted for 70 years (i.e. 1693; see Figure 2). After 1700, there were a series of smaller crises which culminated in the major mortality of 1729 when the deaths were largely confined to adults; we suggest that these acted as perturbations that re-boosted the 30-year cycle which then decayed again although it continued until the population boom began in 1770 and swamped the endogenous oscillation.

Mathematical modelling

Leslie demonstrated how animal populations could be modelled by the use of matrices and important information could be gleaned therefrom. This mathematical technique is applicable to human communities[20] and running the model shows that if the population were hit with a mortality crisis in which a quarter of the population were killed indiscriminately, endogenous cycles in both births and deaths would be triggered. The important points to note are that these cycles would rise and fall together (i.e. they are synchronous) and the period (wavelength) of both cycles would be 43 years.

Actual 43-year cycles in communities of different size in preindustrial England

Did such 43-year endogenous cycles in both births and deaths predicted by the modelling actually occur in communities in preindustrial England? They are difficult to find because, apparently, the population would have to be perturbed by a major mortality crisis and the parish register series presents a confused picture owing to one or more exogenous cycles that were operating simultaneously. Nevertheless, we have been able to show with the aid of time-series analysis that the plague in Penrith in 1598/9 triggered powerful, endogenous, synchronous cycles in baptisms and burials which had a wavelength of 43–44 years and which persisted for 150 years until the community ceased to operate under density-dependent constraints and a population boom began which swamped the endogenous oscillations.[21]

The city of York also suffered severely from an outbreak of plague in 1604 when more than 25 per cent of the population died, and time-series analysis of the registers shows that this mortality crisis triggered synchronous, 46-year cycles in both baptisms and burials.[22] Kirkoswald, a small community in the Eden Valley, Cumbria suffered from the plague in 1598/9 which caused heavy mortality. Unfortunately, the parish records are not complete which makes analysis difficult. However, there is a 44-year cycle in baptisms which is detectable by time-series analysis for the period 1680–1812; the comparable cycle in burials is weak but the two oscillations are significantly synchronous. The Great Plague of London in 1665, with its devastating mortality also generated 44-year cycles in both burials and baptisms.[23]

The foregoing are examples of endogenous cycles in both baptisms and burials from very different-sized populations ranging from a tiny community (Kirkoswald) through a market town (Penrith) and a major city (York) to the metropolis. Time-series analysis shows that they all have approximately the same wavelength, around 44 years, apparently independent of population size, corresponding with the 43-and 44-year cycles described above.

Why is the wavelength of the endogenous cycles about 43 years?

The matrix modelling briefly described above has been developed to include such features as density-dependent pressures (termed feed-back) and the effects of migratory movements.[24] The model was then run, varying the different demographic parameters so as to discover which were the most important factors that determined the wavelength of the endogenous oscillations. In summary, the average fertility of the women during the child-bearing years (termed the fertility distribution) proved to be the most important determinant; 43-year, stable, synchronous cycles in births and deaths were generated after a mortality crisis when the mean of the fertility distribution was set at 30 years in the model. Raising the mean age at which women had their median child to 32 years increased the wavelength of these non-decaying cycles to 44 years whereas reducing the mean of the fertility distribution to 28 years decreased the wavelength to 40 years.[25]

Density-dependent forces were also critical for the generation of the synchronous, 43-year cycles. No change in the wavelength of the endogenous oscillations was found if the feedback was changed over a wide range, but if the model population had only low-level density-dependent constraints on its dynamics, the cycles decayed rapidly and their wavelength fell to 30 years. Thus, the character of the endogenous oscillations changed completely to a simple decaying cycle with a wavelength equal to the mean of the fertility function that was included in the model, replicating the cycle described at Walton-le-Dale above. We suggest, therefore, that the population dynamics at Walton-le-Dale (where only the 30-year, decaying oscillation was found following a mortality crisis) differed from those at Penrith (where both 30 and 43-year cycles were present) because only very low-level density-dependent factors were operating at Walton-le-Dale.

To conclude: modelling suggests that the synchronous, endogenous oscillations in birth and deaths that can be discerned in single populations living under density-dependent constraints during the seventeenth century were triggered by a mortality crisis. If the dynamics were not governed by density-dependent constraints the cycles would have a wavelength equal to the mean of the fertility function and would decay. However, when density-dependent constraints were operating strongly the wavelength of the cycles was increased so that, with a mean of the fertility function (when the women, on average, were having their middle child) of 30 years, the predicted wavelength of the synchronous cycles in births and deaths is 43 years. These endogenous cycles that have been detected reflect the interaction of the demographic parameters of the population (i.e. the fertility function) and the intensity of the density-dependent constraints.

NOTES

1. R. Easterlin, *Population, labor force and long swings in economic growth: the American experience*, (National Bureau for Economic Research, 1968).
2. R.D. Lee, 'The formal dynamics of controlled populations and the echo, the boom, and the bust', *Demography*, **11**, (1974) 563–85; R.D. Lee, 'Population dynamics of humans and other animals', *Demography*, **24**, (1987) 443–65; D. Herlihy, 'Deaths, marriages, births and the Tuscan economy (c.

1300–1550)', in R..D. Lee ed., *Population patterns in the past* (New York, 1977), 135–64; E.A. Wrigley and R.S. Schofield, *The population history of England 1541–1871: a reconstruction,* (London, 1981), 412–21.

3. Lee, 'Formal dynamics', 563–85.
4. Herlihy, 'Deaths, marriages', 135–64; Lee, 'Formal dynamics', 564–5, 582.
5. Herlihy, 'Deaths, marriages', 135–64.
6. Lee, 'Formal dynamics', 582.
7. Lee, 'Formal dynamics', 582; Lee, 'Population dynamics', 443–65.
8. K.W. Wachter and R .D. Lee, 'US births and limit cycle models', *Demography*, **26** (1989), 99–115.
9. R. Easterlin, *Birth and fortune*, (Basic Books, 1980).
10. Lee, 'Formal dynamics', 563–85; K.W. Wachter, 'Elusive cycles; are there dynamically possible Lee-Easterlin models for US births?', *Population Studies*, **45**, (1991), 109–35.
11. Lee, 'Formal dynamics', 565.
12. Lee, 'Population dynamics', 443–65.
13. Lee, 'Formal dynamics', 563–85; Wachter and Lee, 'US births', 99–115.
14. J. Frauenthal and K. Swick, 'Limit cycle oscillations of the human population', *Demography*, **20** (1983), 285–98.
15. Wachter and Lee, 'US births', 100, 113.
16. 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', *Journal of Theoretical Biology*, **158**, (1992), 293–311.
17. S. Scott and C.J. Duncan, *Human demography and disease*, (Cambridge, 1998), 64–65.
18. Wrigley and Schofield, *Population history of England*, 233.
19. S. Scott and C.J. Duncan, 'The mortality crisis of 1623 in north-west England', *Local Population Studies*, **58**, (1977), 14–25.
20. In brief, the demographic characteristics of the population are built into a matrix, the basis of which is a state vector with 50 entries which describes the number of women in each age group from 0 to 50 years. This mathematical model then traces this distribution for 50 successive years. Mortality and fertility will influence the change in numbers in successive years and appropriate values for these factors for the different age groups can be built into the model.
21. Scott and Duncan, *Human demography and disease*, 38–47.
22. We are grateful to Dr. C. Galley for providing us with the data for York.
23. Scott and Duncan, *Human demography and disease*, 186–7.
24. S.R. Duncan, S. Scott and C.J. Duncan, 'Determination of a feedback vector that generates a non-decaying oscillation in a model population', *Journal of Theoretical Biology*, **167** (1994), 67–71.
25. It is the mean and not the standard deviation of the fertility distribution that is of most importance in determining the wavelength of these endogenous cycles.