Biological Determinants of Demographic Processes

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A review and discussion of various analytic and computer simulation models of population growth, with special emphasis on biological factors, is presented.

Introduction

Demographic research is concerned primarily with measuring, explaining, and predicting population characteristics. Variations in economic, psychological, or sociological factors have been introduced most frequently as explanatory influences. For example, the relationship between socioeconomic status and fertility has been examined in detail in a number of studies. In addition, there has been a trend, one which has been increasing in recent work, toward incorporating variations in biological factors as determinants of demographic processes. In formal, or mathematical, demography, a series of population models, developed over the past half century, have included successively more variables which may be thought of as biological in nature. This paper is intended as a review of analytic and computer stimulation models in this category and their applications.

Formal demography has been directed toward describing population growth in a mathematical form, finding some way to express either population size or numbers of births as a function of population characteristics at a previous period. A number of purposes have been served by these models. First, they tried to describe the past as simply and concisely as possible. This is, therefore, their data-fitting function. Viewed as theories of how populations actually do grow and change, they have been used to project or predict future population, a goal Nathan Keyfitz[1] termed the "trisecting the angle" of demography. Like the efforts of mathematicians to trisect the angle, most attempts by demographers to predict population change have failed. However, as a byproduct, demographers learned a great deal about actual population processes. A third purpose or application of a model has been to consider the possible effects on future population of alterations in the influential characteristics. For example, the demographic consequences of a reduction in infant mortality can be examined by means of a model. Work of this type has been particularly valuable in view of the difficulties in conducting meaningful demographic experiments in human populations.

Formal demography can, then, be viewed as one of the many types of model building, as an abstraction of a real process in which the features treated as determinants of that process are, hopefully, realistic. Over the past half century, demography has moved in the direction of including an increasing number of factors as relevant and necessary to achieve a realistic description of population processes.

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Growth Curves

Some 50 years ago, Raymond Pearl and Lowell Reed[2] were enthusiastic proponents of growth curves, attempting to fit observed data on population size at successive censuses by a function and extrapolate future growth from the fitted one- or two-parameter curve. Up until 1920, the fit of the U.S. population to a logistic was excellent. However, when this curve was extrapolated beyond 1920, it failed abysmally to forecast later population size. The rates of overall growth of the population were changing. The growth curve models were all based on the assumption that change in population size was a constant function of its current total size. This type of model has been explored extensively by ecologists,[3] who have developed models of one, two, or more species. The rate of change can depend upon the numbers of members of each of the other species in the system as well as the count of the given species. In this way, ecological models of the relationships between predator and prey and between symbiotic or competitive species have been developed. A fundamental characteristic of these models is the lack of differentiation of individuals by age within the group. This may be fine for amoebae in which, I understand, fission may not be dependent upon the length of time since the last splitting. Or, again, it is appropriate when the proportion of the population in various groups at risk of reproduction or death is relatively fixed. However, it is probably an oversimplification when applied to human populations.

Stable Population Theory

Sharpe and Lotka,[4,5] early in this century, developed an integral equation approach to numbers of births. Leslie,[6] in the 1940s, approached the problem of population size and age composition by matrix methods. Both introduced age-specific birth and survival rates into their mathematical models, formalizing earlier usage of this type of analysis in population projections.[7-9] They demonstrated that, because birth and death rates vary by age, insight into the processes of demographic growth and change would be gained by introducing these factors and current age composition explicitly into their descriptive models. The Leslie method of population projection, the so-called component projection technique, has been used until recently for almost all national population projections.

Lotka[4] went on to develop stable population theory, inquiring into the effect of birth and death rates which remained constant over time. He showed that the age composition of the population would approach a constant form, as would the growth rate. More recently, Ansley Coale[10] hypothesized that if two populations with different initial age distributions began, at a certain point, to be exposed to the same set of age-specific birth and death rates, not necessarily constant over time, their age distributions would tend to become the same. Coale has described this as populations "forgetting their past." Later, Lopez[11,12] provided a rigorous proof of this hypothesis. Keyfitz[12a] and Coale[12b] summarized and extended work in these areas.

No one believes that any population actually experiences unchanging birth and death rates. However, in some cases the changes are small enough so that by assuming that the populations have been relatively stable, demographers have been able to apply stable population theory to develop methods of estimating population characteristics in areas for which the data would otherwise have been considered totally inadequate.

Determinants of Mortality Rates

In all of this work, the primary factors in population growth are the age-specific probabilities of death and of giving birth. The further consideration of these problems is to treat mortality and fertility rates as dependent variables and examine their determinants. Some attempts to do so from a demographic, rather than a medical or public health, viewpoint have been made. Coale and Demeny[13] classified a large number of sets of age-specific mortality rates by country into patterns which appeared typical of various regions of the world. Preston, Keyfitz, and Schoen,[14] in a recent book, collected data on cause-specific mortality rates in a large number of countries, less developed and developed, with reasonably good reporting. They examined the effect on age-specific mortality and life expectancy of eliminating certain causes of death. Their results quantified the differential impact of each of these causes, thus providing both a measure of the importance of each factor and a guide for establishing public health policy.

Determinants of Fertility Rates

It is obvious from stable population theory that when mortality is low, population size and age distribution are determined primarily by fertility rates. That is, fertility, far more than mortality, is the controlling factor in most of the world today. With this realization has come increased interest in the determinants of birth rates. Consequently, studies into how birth rates have changed in the past and how they might be influenced in the future seem in order. One step was to consider the effect of marriage patterns on fertility. This has been a step further toward a biological approach because marriage can be taken (often simply because it is the only relevant data available) as determining entry into exposure to the risk of conception. In the European Fertility Project,[15] a collaborative effort which is attempting to document fertility change from historical records in the countries of Europe, province by province, over 700 in all, demographers are gathering data on proportions married in each age group of women and data on the fertility of married women (marital fertility rates) and of unmarried women (illegitimacy rates). They are investigating the extent to which fertility changes resulted from the adoption of the so-called European pattern of relatively late marriage and relatively high proportions of the population never marrying, and from declines in fertility within marital categories.

Age at marriage, so long as marriage occurs after the onset of the biological capacity of a girl to conceive, can be considered one determinant of the duration of the reproductive period. Increasing age at marriage may produce a substantial reduction in the numbers of children born to a given woman or a given couple due to a shorter effective reproductive period. Ron Lesthaeghe,[16] therefore, calculated what would happen if, in countries with high birth rates and patterns of very early marriage such as are typical in much of Northern Africa, custom changed so that women married at the later ages customary in 19th century Europe. Assuming that nearly all fertility was restricted to legal unions, such a change in nuptiality would induce large declines in birth rates, but not nearly enough to reduce fertility to western European levels.

Large differences in marital age-specific birth rates among noncontracepting populations also exist.[17] These differences could not be explained by differential sterility, either primary or secondary, or, completely, by differences in age at marriage. Therefore if, in approximately the same reproductive period, different populations produced different numbers of children, then the spacing between children must have varied. So the focus of analysis became the birth interval and the variation in factors determining its length.

A further argument for focusing upon the biological factors influencing birth intervals was provided by Davis and Blake,[18] who described a conceptual framework for studying fertility in which they claimed that psychological, social, and economic influences on fertility all must be mediated through the effect of these variables on a set of intervening variables directly affecting fertility and which can be considered as a set of biological determinants of birth intervals. Most studies of the determinants of reproduction by demographers, have, until recently, ignored these intervening variables. The rationale behind the work of mathematical demographers like Louis Henry in France, and Mindel Sheps and Robert Potter in the U.S., among others, is that it will be difficult to interpret reactions of fertility to indirect influences until the relationships between fertility and the variables that are its direct determinants are understood.

Birth Intervals

Intervals between live births may be split up into several segments—the postpartum period following a birth during which either ovulation or sexual relations have not been resumed, the susceptible period during which a woman or couple is exposed to the risk of pregnancy, and then, following conception, a period of gestation which, if pregnancy ends in a live birth, completes the interval. Otherwise, if spontaneous or induced abortion occurs, the woman usually becomes susceptible again after a brief postpartum period. Periods of susceptibility and nonsusceptibility alternate until the live birth that ends the interval occurs. This scheme is important to our thinking about the ways in which family planning programs affect birth rates. Abortion increases the number of infertile pregnancies intervening between successive live births, whereas contraception extends the period during which a couple is exposed to the risk of conception. The time to conception is thought to be determined by fecundability, a concept introduced by Corrado Gini[19] to denote the probability that a woman will conceive in a month when she is susceptible. The action of a contraceptive is to reduce this probability.

Louis Henry and Mindel Sheps have been the primary mathematical analysts of the effects of all of these factors, taken together, in determining birth intervals and birth rates among women living in a continuing sexual union. Starting in 1953, Henry[20] wrote a series of brilliant papers, which were unfortunately little known to the English-speaking world, analyzing via integral equation models the effect that various determinants (including fecundability, the duration of the nonsusceptible periods, and marital duration) have on birth rates. He considered the best ways of estimating these factors from genealogical data. Perrin and Sheps[21] presented a model of reproduction as a Markov renewal process. Their model, the first to apply this kind of stochastic process to demography, also allowed a number of different types of pregnancy outcome to be considered simultaneously. In particular, induced and spontaneous abortion could be treated separately. Certain types of heterogeneity or variation, among women or over time, could be introduced through their model. A number of later papers by Sheps and others extended this model.[22-24]

Both Henry and Sheps provided analytic expressions as part of their results which, under restricted assumptions about changes in reproductive capacity with age and between women, related the various factors to the birth interval and birth rate and showed that, asymptotically, the birth rate approaches the inverse of the mean birth interval.

These models are concerned with a small number of related, interacting parts of the reproductive process rather than all parts of the demographic process. In addition, they are highly simplified and admittedly unrealistic in many respects. Yet they provide insights into the relationships between these factors and birth rates. The models highlight the importance of the duration of the nonsusceptible period after a birth when a woman is unable to conceive because of the suppression of ovulation. Because this duration increases with the duration of lactation, they raised a number of questions about the biological effect of continuing lactation on the resumption of ovulation. They also indicate that, in the absence of contraception, high rates of pregnancy wastage (spontaneous or induced abortion) have surprisingly little effect on birth rates. The models also provided an improved basis for certain types of prediction. Thus, the possible effects of specified changes in contraceptive behavior or in the frequency of induced abortion can now be assessed more reliably.

More generally, some of the implications of specific population policies and programs can be evaluated. Estimates of changes in birth rates, completed fertility, or natality indices to be expected when a given amount and type of behavior change occurs in the population might be made; relations between the social costs and the benefits of various programs could be studied.[25] In addition, the meaning of a program for an individual can be considered. For example, although a certain contraceptive might reduce the birth rate of users by 90 per cent, it might still leave a more than 50 per cent chance of at least one undesired pregnancy in the course of 10 years. Hence, this measure might have serious defects for individuals while, perhaps, achieving desired social goals.

Model building of this type also stimulates precise thinking about the determinants of the process in question, and helps locate the areas in which better information is crucial, for example, the need for information on the nonsusceptible periods.

Demographic models have also played an important role in developing methods of measuring natality by providing a more precise way of studying the reaction of a specific measure to different underlying determinants of fertility.

Other Models of Reproduction

Perhaps the most important role of these models has been to stimulate further work. At least three different types of extensions of models of reproduction have been developed, two in the direction of more complex sets of assumptions about the biological factors. In the first of these, a number of demographers have developed models for parts of the reproductive process, either for a birth interval or for components of the birth interval. The second approach has been to reduce the severe restrictions on assumptions that were necessary for the derivation of analytic results and introduce many more factors by turning to the development of simulation models of reproduction, either through macro- or microsimulation. Finally, other mathematical demographers have incorporated simplified versions of the models for biological aspects of reproduction into analytic models that also consider other determinants of population growth such as marriage and mortality.[26] In addition to the work on reproduction, descriptions of the nonbiological aspects of demographic processes, including marriage[27] and divorce,[28] in mathematical form are being proposed.

Of the models for components of the birth interval, those for fecundability have perhaps the longest history, predating by many years the models thus far discussed. Gini,[19] Raymond Pearl,[29] Stix and Notestein,[30] and many others attempted to measure fecundability through various estimation procedures, usually assuming that all women in their studies shared a common value of this quantity. Tietze[31] and Potter[32] demonstrated that, under the more realistic supposition that fecundability varies among women, the commonly used measures would be sensitive to this variation and to the duration of the follow-up period of observation for pregnancies. Potter and his coworkers[33] have attempted to develop estimation procedures that would take variation in fecundability into consideration and Sheps and others attempted,[23] later, also explicitly to consider the duration of follow-up. Potter et. al.[34] also demonstrated that the distribution of the women who are still susceptible to conception a specified time after this period has begun are a selected sample from the group of all women—selected for lower values of fecundability since the more fecund women conceive earliest in the study. More recently, he has studied the postpartum period and, with Ginsberg and Masnick, analyzed data collected by Perez in Chile[35] on resumption of ovulation after a live birth in relation to duration and extent of lactation. They have developed a three-stage model[36] of the return of ovulation which appears to fit their data relatively well and indicates the kind of studies, combining both new biological observations and demographic analysis, which I believe are necessary and productive in this area. Potter, with others,[37,38] has also looked into the relationship between the postpartum period and the effect of contraceptive use. The IUD has commonly been inserted shortly after a woman delivers a baby. The IUD is also frequently expelled or removed for medical reasons within rather short periods after its first insertion. Therefore, unlike the continuing use of contraception, its effect depends upon the length of time that the woman is willing to or can use the device. If the first part of the insertion time overlaps with the nonsusceptible period, then the effect of the IUD in prolonging the birth interval is reduced. Potter has developed models analyzing the changes in birth intervals according to the timing of the introduction of contraception of various types. In much of this work, he has extended to new areas the renewal theory type of analysis suggested by Sheps and Perrin.

In another conceptually related project, Frederic Abramson[39] has inserted into the Perrin-Sheps model values derived from his study of the duration of pregnancy before spontaneous or induced abortion and concluded that, if pregnancies of this type are very short, very high rates of abortion can mask as slightly lower fecundability without producing easily detectable disturbances in the distribution of birth intervals.

In another direction, Ridley and Sheps[40] developed REPSIM, a cohort microsimulation model which incorporated many of the features of the analytic model with less restrictive assumptions, in particular allowing for much more variation in the biological determinants among women and allowing for aging to alter some of the values. It also permitted mortality and widowhood, a distribution of age at marriage, and a distribution of desired family size. Simulation models produce numerical results for specific sets of input parameters, unlike the analytic models which yield mathematical expressions relating the factors. The analysis of the results from this type of model can be as detailed as one wishes, limited only by the ingenuity and time of the programmer. Studies impossible within the restrictions of an analytic model can be undertaken with these computer models, including far more detailed studies of alternative family planning strategies. Other cohort models have been developed in a number of countries, including those in England by Barrett,[41] in Sweden by Hyrenius and Holmberg,[42,43] in France by Jacquard, Leridon, and Bodmer,[44-46] and in the U.S. by Potter and Sakoda.[47] Many of the features of these models are incorporated into POPSIM,[48] a model that simulates an entire population and contains, in its various versions, more or less explicit biological components.

The models briefly described here lend themselves to the study of significant, though limited, aspects of demographic processes. They have helped demonstrate the importance of certain biological determinants of human populations. Yet much is unknown about these factors themselves. The construction of more and more elaborate models is costly and time consuming and may reduce to an academic exercise unless further research provides crucial new information on the aspects of reproduction and mortality in humans which affect population characteristics.

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