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The Space and Strategy of Demographic Growth

1.1 Humans and Animals

Throughout human history, population has been synonymous with prosperity, stability, and security. A valley or plain teeming with houses, farms, and villages has always been a sign of well-being. Traveling from Verona to Vicenza, Goethe remarked with pleasure: “One sees a continuous range of foothills ... dotted with villages, castles and isolated houses ... we drove on a wide, straight and well-kept road through fertile fields ... The road is much used and by every sort of person.”¹ The effects of a long history of good government were evident, much as in the ordered Sienese fourteenth-century landscapes of the Lorenzetti brothers. Similarly, Cortés was unable to restrain his enthusiasm when he gazed over the valley of Mexico and saw the lagoons bordered by villages and trafficked by canoes, the great city, and the market (in a square more than double the size of the entire city of Salamanca) that “accommodated every day more than sixty thousand individuals who bought and sold every imaginable sort of merchandise.”²

This should come as no surprise. A densely populated region is implicit proof of a stable social order, of non-precarious human relations, and of well-utilized natural resources. Only a large population can mobilize the human resources necessary to build houses, cities, roads, bridges, ports, and canals. If anything, it is abandonment and desertion population rather than abundant population that has historically dismayed the traveler.

Population, then, might be seen as a crude index of prosperity. The million inhabitants of the Paleolithic Age, the 10 million inhabitants of the Neolithic Age, the 100 million inhabitants of the Bronze Age, the billion inhabitants of the Industrial Revolution, or the 10 billion inhabitants that we may attain by mid-twenty-first century certainly represent more than simple demographic growth. Even these few figures tell us that demographic growth has not been uniform over time. Periods of expansion have alternated with others of stagnation and even decline; and the interpretation of these, even for relatively recent historical periods, is not an easy task. We must answer questions that are as straightforward in appearance as they are complex in substance: Why are we 8 billion today and not more or less, say 100 billion or 100 million? Why has demographic growth, from pre-historic times to the present, followed a particular path rather than any of numerous other possibilities? These questions are difficult but worth considering, since the numerical progress of population has been, if not dictated, at least constrained by many forces and obstacles that have determined the general direction of that path. To begin with, we can categorize these forces and obstacles as biological and environmental. The former is linked to the laws of mortality and reproduction that determine the rate of demographic growth, and the latter determines the resistance that these laws encounter and further regulates the rate of growth. Moreover, biological and environmental factors affect each other reciprocally and so are not independent of each other.

Every living collectivity develops particular strategies of survival and reproduction, which translate into potential and effective growth rates of varying velocity. A brief analysis of these strategies will serve as the best introduction to consideration of the specific case of the human species. Biologists have identified two large categories of vital strategies, called r and K , which actually represent simplifications of a continuum.³ Insects, fish, and some small mammals practice an r strategy: these organisms live in generally unstable environments and take advantage of favorable periods (annually or seasonally) to reproduce prolifically, even though the probability of offspring survival is small. It is just because of this environmental instability, however, that they must depend upon large numbers

because “life is a lottery and it makes sense simply to buy many tickets.”⁴ *r* strategy organisms go through many violent cycles with phases of rapid increase and decrease.

A much different strategy is practiced by *K*-type organisms – mammals, particularly medium and large ones, and some birds – that colonize relatively stable environments, albeit populated with competitors, predators, and parasites. *K* strategy organisms are forced by selective and environmental pressure to compete for survival, which in turn requires considerable investment of time and energy for raising offspring. This investment is possible only if the number of offspring is small.

r and *K* strategies characterize two well-differentiated groups of organisms (Figure 1.1). *r* strategies are suited to small animals having a short life span, minimal intervals between generations, brief gestation periods, short intervals between births, and large litters. *K* strategies, on the contrary, are associated with larger animals, long life spans, long intervals between generations and between births, and single births.

Figure 1.2 records the relation between body size (length) and the interval between successive generations for a wide array of living organisms: as the first increases, so does the second. It can also be demonstrated that the rate of growth of various species (limiting ourselves to mammals) varies more or less inversely with the length of generation and so with body size.⁵ At an admittedly macroscopic level of generalization, the lower demographic growth potential of larger animals can be linked to their reduced vulnerability to environmental fluctuations, and this, too, is related to their larger body size. Because their life is not a lottery and their chances of survival are better, the larger animals do not need to entrust the perpetuation of the species to high levels of reproduction. The latter, in fact, would detract from those investments of protection and care required to ensure the offspring’s reduced vulnerability and keep mortality low.

These ideas have been well known at least since the time of Darwin and Wallace, founders of the theory of natural selection. Nonetheless, they provide a useful introduction to the discussion of the factors of human increase. Our species obviously practices a *K* strategy, in that

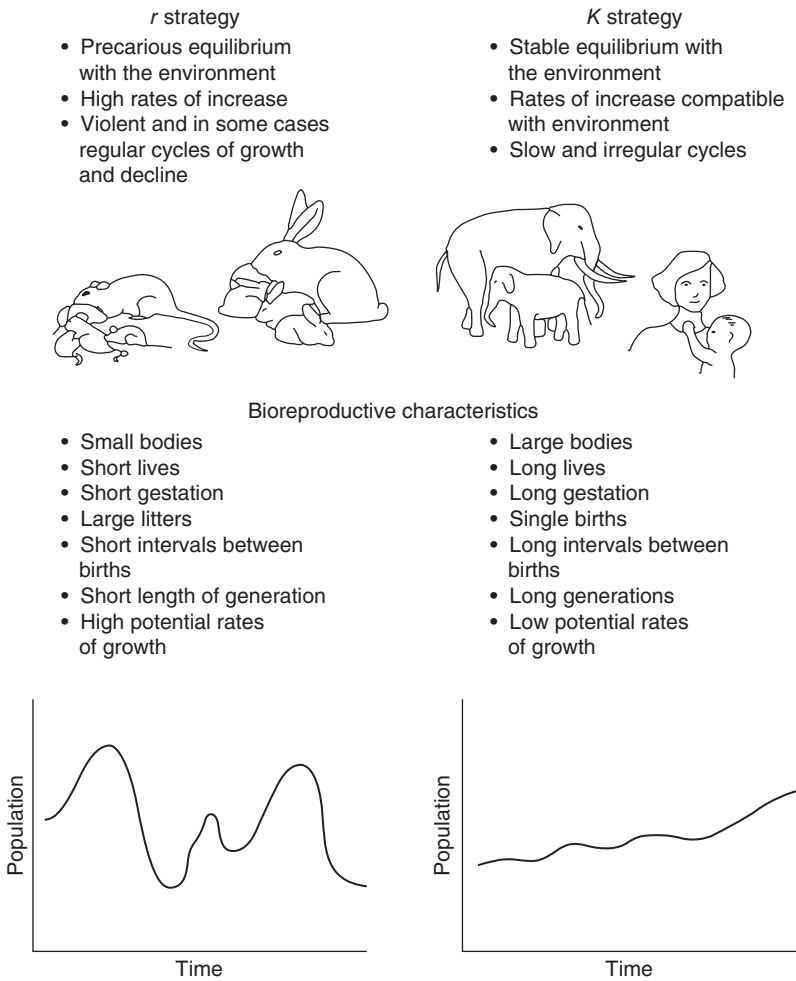


Figure 1.1 *r* strategy and *K* strategy.

it has successfully controlled the fluctuating environment and invests heavily in the raising of its young.

Two principles will be particularly helpful for confronting the arguments in the following pages. The first principle concerns the relation between population and environment; this should be understood broadly to include all the factors – physical environment, climate, availability of food, and so on – that determine

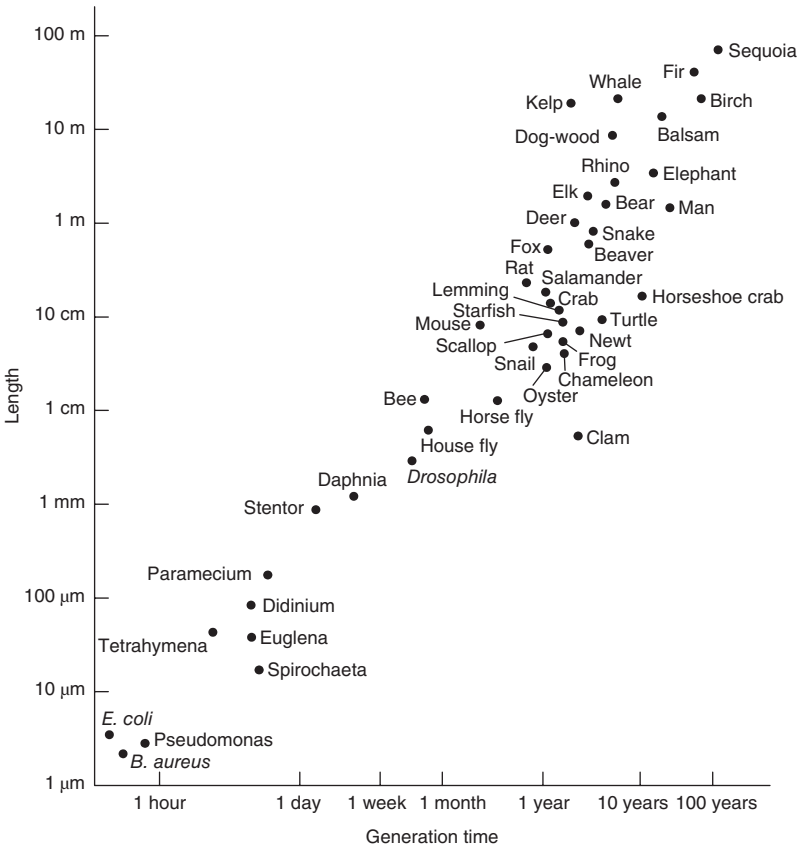


Figure 1.2 The length of an organism at the time of reproduction in relation to the generation time, plotted on a logarithmic scale. *Source:* J. T. Bonner (1965) / with permission of Princeton University Press.

survival. The second principle concerns the relation between reproduction and mortality insofar as the latter is a function of parental investment, which in turn relates inversely to reproductive intensity.

1.2 Divide and Multiply

Many animal species are subject to rapid and violent cycles that increase or decrease their numbers by factors of 100, 1,000, 10,000, or even more in a brief period. The four-year cycle of the Scandinavian

lemming is well known, as are those of the Canadian predators (10 years) and many infesting insects of temperate woods and forests (4–12 years). In Australia, “in certain years the introduced domestic mouse multiplies enormously. The mice swarm in crops and haystacks, and literal bucketfuls can be caught in a single night. Hawks, owls and cats flourish at their expense . . . but all these enemies have little effect in reducing the numbers. As a rule the plague ends rather suddenly. A few dead mice are found on the ground and the numbers dwindle rapidly to, or below, normal.”⁶ Other species maintain equilibrium. Two centuries ago, Gilbert White observed that eight pairs of swallows flew around the belfry of the church in the village of Selborne, just as is the case today.⁷ There are, then, both populations in rapid growth or decline and populations that are more or less stable.

The human species varies relatively slowly over time. Nonetheless, as we shall see in Section 1.7, long cycles of growth do alternate with others of decline, and the latter have even led to extinction for certain groups. For example, the population of Mesoamerica was reduced to a fraction of its original size during the century that followed the Spanish conquest (initiated at the beginning of the sixteenth century), while that of the conquering Spaniards grew by half. Other populations have disappeared entirely or almost entirely – the population of Hispaniola (modern Haiti and Dominican Republic) after the landing of Columbus or that of Tasmania following contact with the first explorers and settlers – while, at the same time, others nearby have continued to increase and prosper. In more recent times, the population of England and Wales multiplied sixfold between 1750 and 1900, while that of France increased by barely 50 percent in the same period. According to estimates, the population of Niger has multiplied 10-fold between 1950 and 2024, while, in the meantime, that of Hungary has remained unchanged.

These few examples should suffice to demonstrate at what different rates the human species can grow even in similar situations (France and England) and over long periods. It should also be clear that here lies the heart of demography as a science: to measure growth, analyze mechanisms, and understand causes.

Population growth (whether positive or negative, rapid or slow) can be described by a simple calculation. In any interval of time, a population (P) varies numerically as a result of renewal or arrivals (births B and immigration I) and elimination or departures (deaths D and emigration E). Leaving aside migration (considering the population “closed,” as is that of the entire planet), the change in population dP in any interval of time t – by convention and for convenience, demographers use years – is given by the following:

$$dP = B - D \quad [1.1]$$

and so the rate of growth r (where $r = dP/P$) will be equal to the difference between the birth rate b (where $b = B/P$) and the death rate d (where $d = D/P$):

$$r = \frac{dP}{P} = b - d \quad [1.2]$$

The range of variation of the birth and death rates is fairly wide. Minimum values are 5–10 per 1,000 (possible today with mortality and fertility under control) and maximum values are 40–50 per 1,000. As mortality and fertility are not independent, it is unlikely that opposite extremes should coexist. Over long periods, growth rates vary in practice between –1 and 3 percent per year.

For most of human history, fertility and mortality must have remained in virtual equilibrium, as the rate of population growth was very low. If we accept the estimates of 252 million for the world population at the beginning of the present era (0 CE) and 771 million in 1750 at the beginning of the Industrial Revolution (Table 1.1), then we can calculate the average annual growth rate for the period as 0.06 percent. If we imagine that mortality averaged 40 per 1,000, then fertility must have been 40.6 per 1,000, just 1.5 percent greater than mortality. Since the 1960s, the situation has been quite different as fertility has exceeded mortality by 200 percent.

Fertility and mortality rates are numerical calculations with little in the way of conceptual content and as such are not well adapted to the description of the phenomena of reproduction and survival on which demographic growth depends.

Table 1.1 Population, total births, and years lived (10,000 BCE to 2000 CE).

Demographic index	10,000 BCE	0	1750	1950	2000
Population (in million)	6	252	771	2,529	6,115
Annual growth (%)	0.008	0.037	0.064	0.594	1.766
Doubling time (years)	8,369	1,854	1,083	116	40
Births (in billion)	9.29	33.6	22.64	10.42	5.97
Births (%)	11.4	41.0	27.6	12.7	7.3
Life expectancy (e_0)	20	22	27	35	56
Years lived (in billion)	185.8	739.2	611.3	364.7	334.3
Years lived (%)	8.3	33.1	27.3	16.3	18.0

Notes: For births, life expectancy, and years lived, the data refer to the interval between the date at the head of the column and that of the preceding column (for the first column the interval runs from the hypothetical origin of the human species to 10,000 BCE).

1.3 Jacopo Bichi and Domenica Del Buono, Jean Guyon, and Mathurine Robin

Jacopo Bichi was a humble sharecropper from Fiesole (near Florence).⁸ On November 12, 1667, he married Domenica Del Buono. Their marriage, although soon ended by the death of Jacopo, nonetheless produced three children: Andrea, Filippo, and Maria Maddalena. The latter died when only a few months old, but Andrea and Filippo survived and married. In a sense, Jacopo and Domenica paid off their metaphoric “debt”: the care received from their parents, and their own resistance and luck, succeeded in bringing them to reproductive age. They in turn bore and raised two children who reached the same stage of maturity (reproductive age and marriage) and who, in a sense, replaced them exactly in the generational chain of life. Continuing the story of this family, Andrea married Caterina Fossi, and together they had four children, two of whom married. Andrea and Caterina also paid their debt. Such was not the case for Filippo, who married Maddalena Cari. Maddalena died shortly afterward, having borne a daughter who in turn died at a young age. The two

surviving sons of Andrea constitute the third generation: Giovan Battista married Caterina Angiola and had six children, all but one of whom died before marrying. Jacopo married Rosa, who bore eight children, four of whom married. Let us stop here and summarize the results of these five marriages (and 10 spouses):

Two couples (Jacopo and Domenica, Andrea and Caterina) paid their debt, each couple bringing two children to matrimony.

One couple (Jacopo and Rosa) paid their debt with interest, as the two of them produced four wedded offspring.

One couple (Giovan Battista and Caterina Angiola) finished partially in debt in spite of the fact that they produced six children; only one of them married.

One couple (Filippo and Maddalena) was completely insolvent, as no offspring survived to marry.

In 3 generations, 5 couples (10 spouses) produced 9 wedded children in all. In biological terms, 10 breeders brought 9 offspring to the reproductive phase, a 10 percent decline that, if repeated for an extended period, would lead to the family's extinction.

A population, however, is made up of many families and histories, each different from the others. In this same period, and applying the same logic, 6 couples of the Patriarchi family married off 15 children, while 5 Palagi couples did so with 10. The Patriarchi paid with interest, while the Palagi just fulfilled their obligation. The combination of these individual experiences, whether the balance is positive, negative, or even, determines the growth, decline, or stagnation of a population in the long run.

In 1608, Québec was founded and the French inhabitation of the St Lawrence Valley, virtually abandoned by the Iroquois, began.⁹ During the following century, approximately 15,000 immigrants arrived in these virgin lands from Normandy, from the area around Paris, and from Central Western France. Two-thirds of them returned to France after stays of varying lengths. The current population of over 7 million French Canadians descends, for the most part, from those 5,000 immigrants who remained, as subsequent immigration

contributed little to population growth. Thanks to a genealogical-demographic reconstruction carried out by a group of Canadian scholars, a considerable amount of information relating to demographic events is known about this population. For example, two pioneers, Jean Guyon and Mathurine Robin, had 2,150 descendants by 1730. Naturally, subsequent generations, including wives and husbands from other genealogical lines, contributed to this figure, which in and of itself has little demographic significance. On the contrary, the fate of another pioneer, the famous explorer Samuel de Champlain, was very different, and he left no descendants at all. The extraordinary Canadian material also provides measures of significant demographic interest. For example, the 905 pioneers (men and women), who were born in France, migrated to Canada before 1660, and both married and died in Canada, produced on average 4.2 married offspring per couple (Figure 1.3), a level of fertility that corresponds to a doubling of the original population in a single generation (from 2 spouses, 4 married children). The exceptionally high reproductive capacity of the settlers of French Canada was the result of an extraordinary combination of circumstances: the physical selection

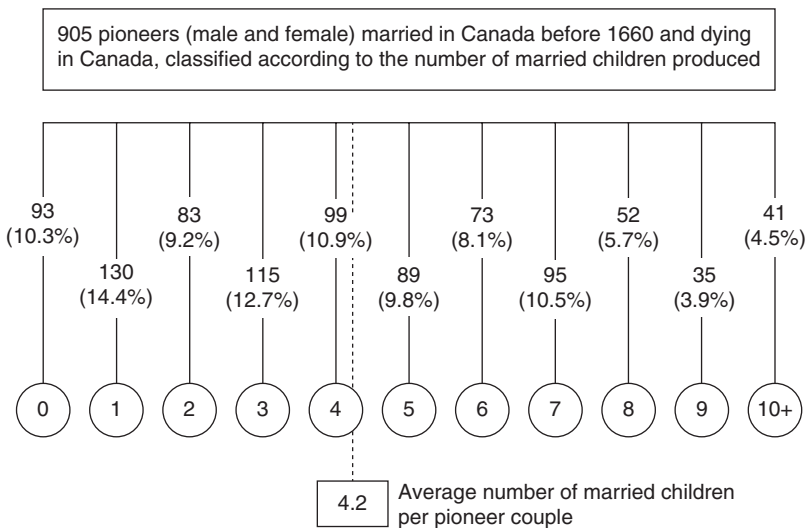


Figure 1.3 Growth of the French Canadian population (seventeenth century): pioneers and their children.

of the immigrants, their high fertility and low mortality, ample available space, low density, and the absence of epidemics.

We have unknowingly touched the heart of the mechanisms of population growth. As we have seen, a population grows (or declines or remains stationary) from one generation to the next if those who gain access to reproduction (here defined by the act of marriage) are in turn successful in bringing a larger (or smaller or equal) number of individuals to marriage. The end result, whatever it might be, is basically determined by two factors: the number of children each individual, or each couple, succeeds in producing – due to biological capability, desire, age at marriage, length of cohabitation, and other factors – and the intensity of mortality from birth until the end of the reproductive period. Familiarity with these mechanisms, which I shall discuss in the following section, is essential for understanding the factors of demographic change.

1.4 Reproduction and Survival

The growth potential of a population may be expressed as the function of two measures, whose significance should be intuitive: (1) the number of births, or children, per woman and (2) life expectancy at birth. These are synthetic measures of, respectively, reproduction and survival. The first measure, the number of births, describes the average number of children produced by a generation of women during the course of their reproductive lives and in the hypothetical absence of mortality.¹⁰ In the following section, we consider the biological, social, and cultural factors that determine the level of this measure. The second measure, life expectancy at birth, describes the average duration of life (or average number of years lived) for a generation of newborns and is a function of the force of mortality at the various ages, which in turn is determined by the species' biological characteristics and relationship with the surrounding environment. In the primarily rural societies of past centuries, which lacked modern birth control and effective medical knowledge, both of these measures might vary considerably. The number of children per woman ranged from less than 5 to more

than 8 (though today, in some Western societies characterized by high levels of birth control, it has declined below 1), and life expectancy at birth ranged from 20 to 40 years (today, it is over 80 years in many developed countries).

The number of children per woman depends, as has been said, on biological and social factors that determine (1) the frequency of births during a woman's fecund period and (2) the portion of the fecund period – between puberty and menopause – effectively utilized for reproduction.¹¹

1.4.1 The Frequency of Births

This is an inverse function of the interval between births. Given the condition of natural fertility – a term used by demographers to describe those premodern societies that did not practice intentional contraception for controlling either the number of births or their timing – the interval between births may be divided into four parts:

- 1) *A period of infertility after every birth*, as ovulation does not recommence for a couple of months. However, this anovulatory period, during which it is impossible to conceive, increases with the duration of breastfeeding, which is often continued until the second, and in some cases even third, year of the child's life. The duration of breastfeeding, however, varies considerably from one culture to another, so that the minimum and maximum limits for the infertility period fall between 3 and 24 months.
- 2) *The waiting time*, that is, the average number of months that pass between the resumption of normal ovulation and conception. It is possible that some women, either for accidental or natural reasons, may conceive during the first ovulatory cycle, while others, even given regular sexual relations, may not do so for many cycles. We can take 5 and 10 months as our upper and lower limits.
- 3) *The average length of pregnancy* is about 9 months.
- 4) *Fetal mortality*. About one out of every five recognized pregnancies does not come to term because of miscarriage. According to the few studies available, this seems to be a frequency that does not vary much from population to population. After a

miscarriage, a new conception can take place after the normal waiting period (5–10 months). As only one in five conceptions contributes to this component of the birth interval, the average addition is 1–2 months.

Totaling the minimum and maximum values of 1, 2, 3, and 4, we find that the interval between births ranges from 18 to 45 months (or approximately 1.5–3.5 years), but, as a combination either of maxima or minima is improbable, this interval usually falls between 2 and 3 years. The above analysis holds true for a population characterized by uncontrolled, natural fertility. Of course, if birth control is introduced, the reproductive life span without children may be expanded at will.

1.4.2 The Fecund Period Used for Reproduction

The factors that determine the age of access to reproduction, or the establishment of a stable union for the purpose of reproduction (marriage), are primarily cultural, while those that determine the age at which the reproductive period ends are primarily biological.

- 1) The age at marriage may vary between a minimum close to the age of puberty – let us say 15 years – and a maximum that in many European societies has exceeded 25 years.
- 2) The age at the end of the fecund period may be as high as 50 years, but on average it is much lower. We can take as a good indicator the average age of mothers at the birth of the last child in populations that do not practice birth control. This figure is fairly stable and varies between 38 and 41 years.

We can say then – again combining minima and maxima and rounding – that the average length of a union for reproductive purposes, barring death or divorce, may vary between 15 and 25 years.

Simplifying still more, we can estimate what the minimum and maximum levels of procreation might be in hypothetical populations not subject to mortality. To obtain the minimum, we combine

the minimum reproductive period (15 years) with the maximum birth interval (3.5 years):

$$\frac{15\text{-year reproductive period}}{3.5\text{-year birth interval}} 4.3 \text{ children}$$

To obtain the maximum level, we instead combine the maximum reproductive period (25 years) with the minimum birth interval (1.5 years):

$$\frac{25\text{-year reproductive period}}{1.5\text{-year birth interval}} 16.7 \text{ children}$$

These combinations of extremes (especially the latter) are of course impossible, as the various components are not independent of each other. Repeated childbearing, which follows early marriage, for example, can create pathological conditions that lower fecundity or else lead to an early decline in sexual activity and so increase the birth interval. In stable historical situations, the average levels of under 5, or over 8 children per woman, are rare.

The number of children per woman depends primarily upon the age at marriage (the principal factor determining the length of the reproductive period) and the duration of breastfeeding (the principal component determining the birth interval). Figure 1.4, adapted from the Bongaarts and Menken article on which this discussion is based, shows how the average number of children per woman can vary as a result of the variation (between maximum and minimum values) of each component. We take as a standard 7 children, obtained by combining average values of the various components. As one component varies, the others remain fixed.¹²

In Figure 1.5, the above model is applied to several historical (and theoretical) examples. In addition to the biological maximum (1), there is a possible maximum (2) resulting from a combination of early marriage (at the age of 18 years) and short birth intervals (due to early weaning); a possible minimum in the absence of birth control (6) resulting from late marriage (at the age of 25 years) and prolonged breastfeeding; three intermediate levels (3), (4), and (5); and finally, examples of medium and very high levels of birth control, (7) and (8), yielding, respectively, 3 and 1 children. These examples should not be

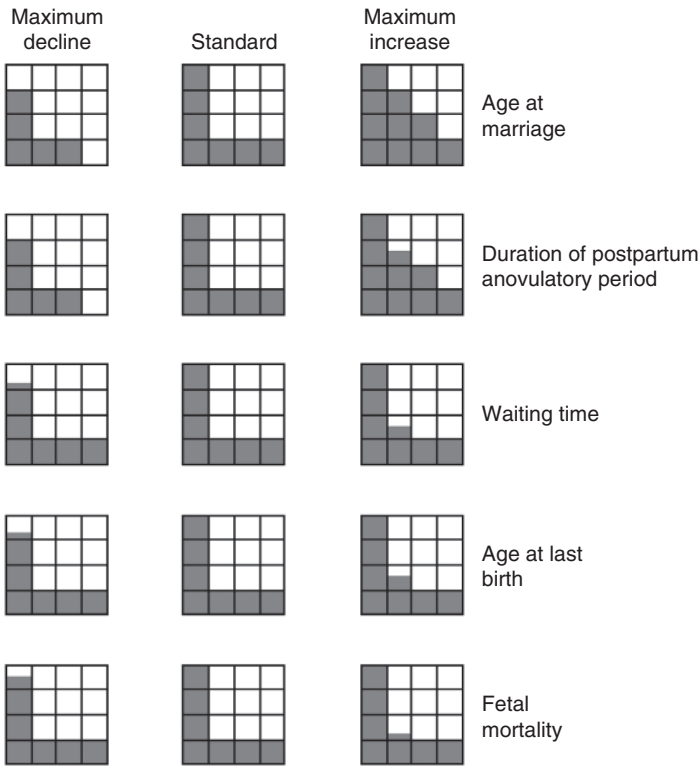


Figure 1.4 Effect on the average number of children per woman of maximum variations of the components of fertility above and below the standard (1 square = 1 birth).

considered to represent a chronological or evolutionary sequence, as almost all can be found in populations living in the same historical periods (except for the last two, characterized by strongly controlled fertility, which can only be found in modern populations).

In addition to the biosocial components determining fertility, human reproductivity must also contend with the hard check of mortality, a factor that we have ignored up to this point. Reproductivity and mortality are not independent of each other for any living species, including humans. When the number of offspring is very large, the risk of death in early infancy increases and the competition for resources within the family can lower resistance at all ages. On the

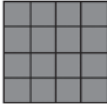
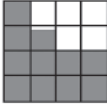
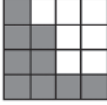
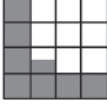
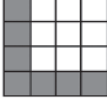
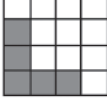
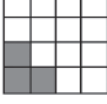
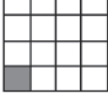
	Children per woman (TFR)	Reproductive space utilized	Characteristics	Populations	Historical example (populations)
(1)	16		Biological maximum	Theoretical	None individual cases only
(2)	11.4		Very early unions minimum intervals	Select groups	French Canadians born before 1660
(3)	9		Late unions minimum intervals	Select groups	Canadian Hutterites, 1926–30 = 8.5
(4)	7.5		Early unions long intervals	Many developing populations	Egypt, 1960–65 = 7.1
(5)	7		Standard		
(6)	5		Late unions long intervals	Many European populations (eighteenth to nineteenth centuries)	England 1751–1800 = 5.1
(7)	3		Voluntary birth control (medium diffusion)	Europe (first half twentieth century)	Italy, 1937 = 3.0
(8)	1		Voluntary birth control (high diffusion)	Several present-day European populations	Liguria (Italy) 1990 = 1.0

Figure 1.5 Fertility models.

contrary, high fertility is, in the long run, incompatible with low, or recently lowered, mortality, given the resultant excessive population growth. Nonetheless, mortality is to a large degree rooted in human biology and so is independent of fertility levels.

A fairly simple way to describe human mortality is provided by the survivorship function, l_x , which traces the progressive elimination of a generation of 10^n individuals from birth to the age at which the last member dies.¹³ Figure 1.6 shows three survivorship curves. The lower curve corresponds to a life expectancy at birth (e_0) of 20 years. This is a very low figure, near to the minimum compatible with the continued survival of a population, and might characterize a primitive population living in a hostile environment. The upper curve corresponds to an e_0 of 83 years, a level that the more-developed countries (Japan, Italy, France, and Spain) have already reached. The third, intermediate curve ($e_0 = 50$) is typical of those countries that have benefited from a limited degree of modern medical progress. In Figure 1.6, I have chosen the maximum age, in all three cases, 100 years, assuming that this is the

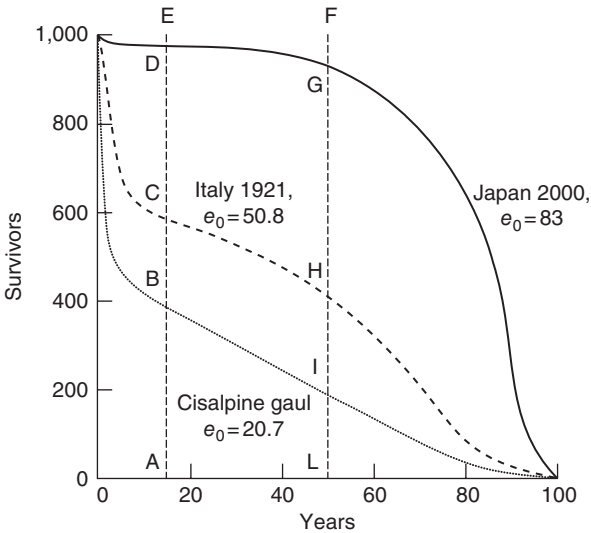


Figure 1.6 Survival curves for three female populations characterized by low, medium, and high life expectancy at birth. *Note:* Survival curves trace the numerical decline with the age of a generation of 1,000 births. Life expectancy at birth is proportional to the space bounded by the ordinate, the abscissa, and the survival curve. The area AEFL, equal to 35 years, describes the length of the reproductive period. The areas ADGL, ACHL, and ABIL, equal to 34.4, 24.8, and 10.2 years, describe the average effective reproductive lives for the three generations of 1,000 newborn girls. The ratios of ADGL/AEFL, ACHL/AEFL, and ABIL/AEFL are 98.2, 70.8, and 29.2 percent, respectively, and represent the average part of the reproductive period lived by the three generations.

limit of human longevity. This assumption is not far from the truth, since less than 2 percent of the initial generation survives to this age.¹⁴ Continuing to refer to Figure 1.6, if we imagine that no one dies until their 100th birthday, at which age everyone dies, then the l_x curve will be rectangular (it will be parallel to the abscissa until the age of 100 years, at which point it will drop vertically to 0) and e_0 will be equal to 100. The life expectancies at birth described by the other curves are proportional to the areas under those curves. The shape of the survivorship curves depends upon the force of mortality at various ages. In human populations, there is a period of high mortality immediately after birth and during early infancy, the result of fragility in the face of the external environment. Mortality risk reaches a minimum during late infancy or adolescence and then, from maturity, rises exponentially as a function of the gradual weakening of the organism. In high-mortality regimes (see the $e_0 = 20$ curve), the curve tends to be concave. As mortality improves, infant mortality becomes less of a factor and the curve becomes more and more convex. From a strictly genetic point of view – the hereditary genetic transmission of characteristics – survival beyond the reproductive years (for simplicity, say 50 years of age) is of course irrelevant. However high or low it might be, the rate of mortality beyond the age of 50 years will have no effect on the genetic patrimony of a population. Before and during the reproductive years, on the contrary, the higher the level of mortality, the stronger the selective effect, as individuals possessing characteristics unfavorable to survival are eliminated and so do not pass on these characteristics to subsequent generations.

Nonetheless, increased survival beyond the reproductive ages may have indirect biological effects, as older adults contribute to the accumulation, organization, and transmission of knowledge, while also favoring parental investments, and so can contribute to the improved survival of new generations.

Figure 1.7 shows two survivorship models typical of other species, together with high- and low-mortality human models. Model A typifies those species that are subject to the relatively constant mortality risk presented by other predatory species, while model B is typical of

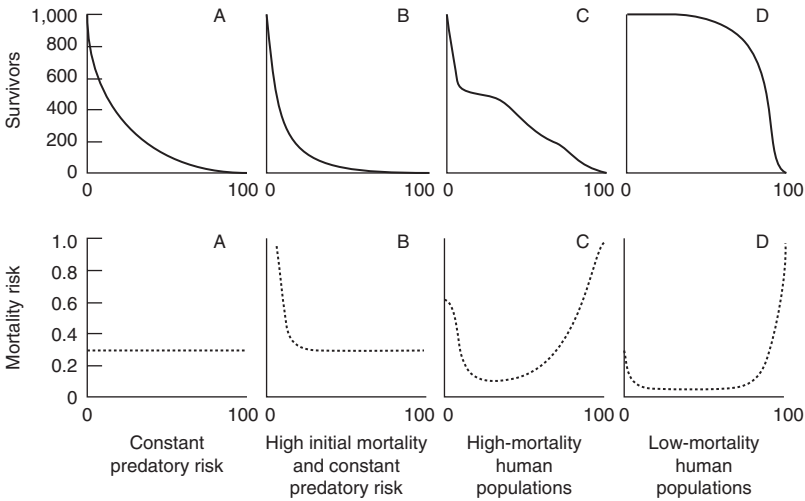


Figure 1.7 Survival models.

those (*r* strategy) species that depend upon prolific reproduction for survival and are subject to very high postnatal mortality.

Let us return to the human species. To appreciate its reproductive capacity, we must understand the laws governing its survival until the end of the reproductive period. Afterward, whether or not an individual survives is theoretically unimportant.¹⁵ From Figure 1.6 we can see that, with life expectancy at birth equal to 20 years, only 29.2 percent of the potential fecund life of a generation is actually lived owing to the decimation caused by high mortality. This proportion increases gradually with increasing life expectancy (and the elevation of the l_x curve). In the examples given, it is 70.8 percent when e_0 equals 50 and 98.2 percent when e_0 equals 83.

It should be clear now that the reproductive success of a population – and so its growth – depends upon the number of children born to those women who survive to reproductive age. If we imagine a level of 6 children per woman in the absence of mortality, then in that case where only 30 percent of the reproductive space is used ($e_0 = 20$) the number of children born per woman is $6 \times 0.3 = 1.8$. When $e_0 = 50$ and 70 percent of the reproductive space is used, the number of children is $6 \times 0.7 = 4.2$; and when 99 percent is used

($e_0 = 83$), the total is $6 \times 0.99 = 5.94$. Since there are two parents for every child, each hypothetical couple pays its demographic debt (and the number of parents and children is about equal) if our calculation above yields a level of two. A number larger than two implies growth. If the number of surviving children is four, then the population will double in the course of a single generation (about 30 years) and the average annual growth rate will be 2.3 percent.¹⁶

1.5 The Space of Growth

Fertility and mortality, acting in tandem, impose objective limits on the pattern of growth of human populations. If we imagine that in a certain population, these remain fixed for a long period of time, then, by resorting to a few simplifying hypotheses,¹⁷ we can express the rate of growth as a function of the number of children per woman (*TFR*) and life expectancy at birth (e_0).

Figure 1.8 shows several “isogrowth” curves. Each curve is the locus of those points that combine life expectancy (the abscissa) and number of children per woman (the ordinate) to give the same rate

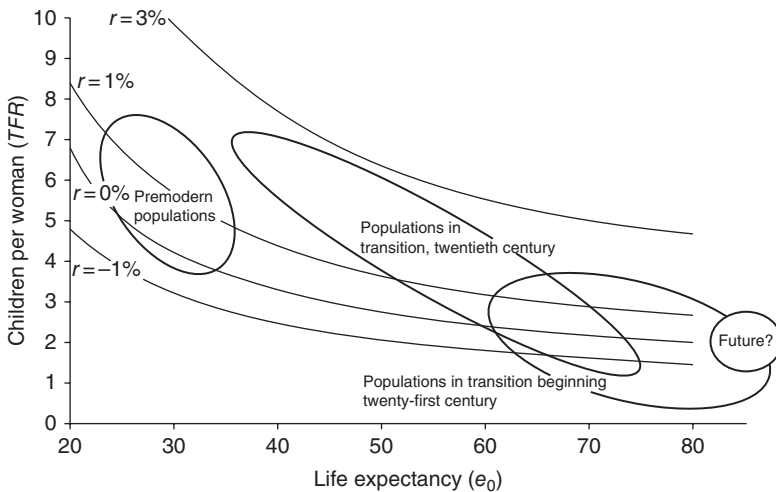


Figure 1.8 Relationship between the average number of children per woman (*TFR*) and life expectancy (e_0) in historical and present-day populations.

of growth r . Included in this graph are points corresponding to historical and contemporary populations. For the former, life expectancy is neither below 15 years, as this would be incompatible with the continued survival of the population, nor above 45 years, as no historical population has ever achieved a higher figure. For similar reasons, the number of children per woman falls between eight (almost never exceeded in normally constituted populations) and four (recall that these are populations that are not practicing birth control). Figure 1.8 reports, left to right, four areas, three ellipses, and one round in shape; each of these areas represents the locus of populations belonging to different epochs. The first ellipse is the locus of historical populations before the Industrial Revolution and the modern diffusion of birth control. These populations fall within a band of growth rates that extends from 0 to 1 percent, a space of growth typical of premodern times. Within this narrow band, however, the fertility and mortality combinations vary widely, although constrained by the syndromic poverty of resources and of knowledge. Denmark at the end of the eighteenth century and India a century later, for example, have similar growth rates, but these are achieved at distant points in the strategic space described: the former example combines high life expectancy (about 40 years) and a small number of children (just over 4), while in the latter case low life expectancy (about 25 years) is paired with many children (just under 7).

Although their growth rates must have been similar, the points for Paleolithic and Neolithic populations are assumed to have been far apart. According to a well-accepted opinion (see Chapter 2), the Paleolithic, a hunting and gathering population, was characterized by lower mortality, owing to its low density, a factor that prevented infectious diseases from taking hold and spreading, and moderate fertility, compatible with its nomadic behavior. For the Neolithic, a sedentary and agricultural population, both mortality and fertility were higher as a result of higher density and lower mobility.

The second ellipse contains the populations during the process of demographic transition in the twentieth century. The strategic space utilized, previously restricted to a narrow band, has expanded dramatically. Medical and sanitary progress has shifted the upper limit

of life expectancy from the historical level of about 40 years to the present level of above 80 years, while the introduction of birth control has reduced the lower limit of fertility to a level of about one child per woman. The third ellipse outlines the situation at the beginning of the twenty-first century, when countries with very high fertility (many in sub-Saharan Africa) coexist with other countries (in Europe and Southern and Eastern Asia) with abnormally low fertility, close to one child per woman. It must be remarked that in the much expanded space of the twentieth and twenty-first centuries, there are populations with implicit growth rates of 4 percent and other populations with negative growth rates of -2 percent. A population with a 4 percent rate of growth doubles in 17–18 years, and that declining at the rate of 2 percent halves in 35 years.¹⁸ Two populations of equal size experiencing these different growth rates will find themselves after 35 years (about a generation) in a numerical ratio of 8:1. However, this is the space of populations in transition, unstable, and often with unsustainable paces of growth. The fourth space, circular in shape, is the hypothetical region of the future, after the transition and at the end of a process of convergence, with an expectation of life above 80 years, fertility between 1 and 3 children per woman, and potential rates of growth between -1 and $+1$ percent. These populations could alternate phases of growth and decline, possibly not synchronized, with relatively small and diluted changes in time.

1.6 Environmental Constraints

Although the strategic space of growth is large, only a small portion of it can be permanently occupied by a population. Sustained decline is obviously incompatible with the survival of a human group, while sustained growth can in the long run be incompatible with the resources available. The mechanisms of growth, therefore, must continually adjust to environmental conditions (which we might call environmental friction), conditions with which they interact but which also present obstacles to growth, as attested to by the millennia during which the population growth rate has been very low. For

the moment, I shall limit myself to the macroscopic aspects of these obstacles to demographic growth, saving for later a more detailed discussion of their operation.

In a justly famous essay, Carlo Cipolla wrote, “It is safe to say that until the Industrial Revolution man continued to rely mainly on plants and animals for energy – plants for food and fuel, and animals for food and mechanical energy.”¹⁹ It is this subordination to the natural environment and the resources it provides that constituted a check to population increase, a situation particularly evident for a hunting and gathering society. Imagine a population that utilizes a habitat extending only to those places that can be reached, and returned from, in a single day’s walk. The abundance of available food depends upon the ecology of the area, the accessibility of resources, and the related costs (so to speak) of extraction and utilization, and this in turn places a check on the number of inhabitants. In the simplest terms, vegetal biomass production (primary productivity) per unit area is a function of precipitation, and animal biomass production (of herbivores and carnivores – secondary productivity) is, in turn, a function of the vegetal biomass, so precipitation is the principal factor limiting both the resources available to hunters and gatherers and their numerical growth.²⁰ Figure 1.9 shows the relation between vegetal biomass and precipitation in various parts of the world, while Figure 1.10 charts the dependence of Australian Aboriginal population density on the intensity of rainfall.

Table 1.2 reports possible values for the population density of hunter–gatherer societies in different ecological systems, according to certain hypotheses regarding biomass and precipitation. This is, of course, only a model, but one that effectively describes a double check on population increase. The first check is imposed by natural limits of vegetal and animal production which define the maximum number of individuals that can be fed. In an area 10 km in diameter, the sustainable population ranges from 3 for an Arctic area to 136 for a subtropical savanna. The second check relates to the incompatibility of very low population density (for example, Arctic and semi-desert areas) with the survival of a stable population group. To ensure a reasonable choice of partners and to survive catastrophic events, these groups must not be too small.

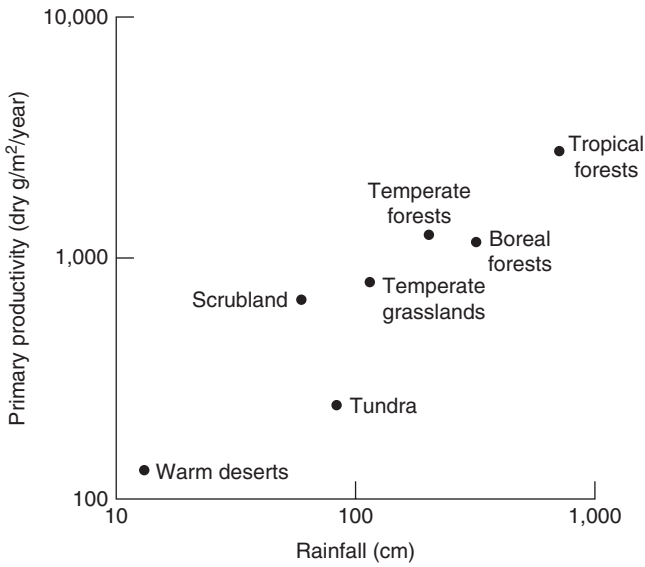


Figure 1.9 Relationship between rainfall and primary productivity for world biomes. *Source:* F. A. Hassan (1981) / with permission of Elsevier.

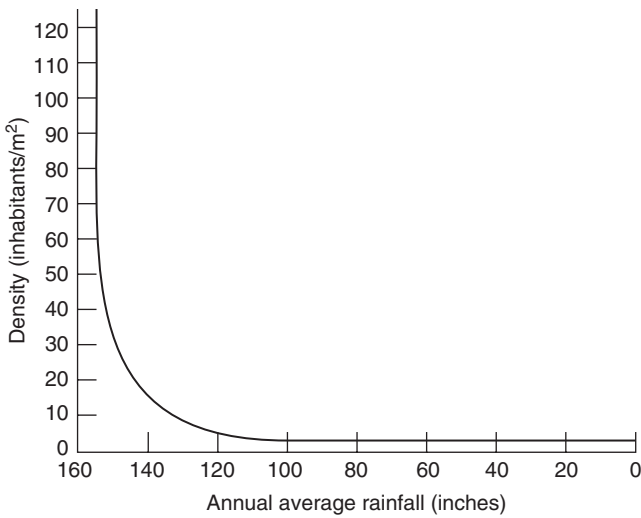


Figure 1.10 Relationship between annual precipitation and population density (Australian Aborigines).

Table 1.2 Estimated population density and size for a catchment territory of 314 km² in different world biomes.

Biome	Biomass (kg/km ²)	Population density (persons per km ²)	Number of persons
Arctic	200	0.0086	3
Subtropical savanna	10,000	0.43	136
Grassland	4,000	0.17	54
Semidesert	800	0.035	11

Source: F. A. Hassan (1981) / with permission of Elsevier.

Archaeological and contemporary observations have placed the density of hunter-gatherer populations at between 0.1 and 1 per km².²¹ Higher densities may be encountered near seas, lakes, and streams, where fishing can effectively supplement the products of the earth. Clearly, the limiting factors at this cultural level are essentially precipitation and the availability and accessibility of land.

The Neolithic transition to stable cultivation of the land and the raising of livestock certainly represented a dramatic expansion of productive capacity. This transition, which many call a “revolution,” developed and spread slowly over millennia in a variety of ways and forms. The progress of cultivation techniques, from slash and burn to triannual rotations (which have coexisted in different cultures up to the present day), the selection of better and better seeds, the domestication of new plants and animals, and the use of animal, air, and water power have all enormously increased the availability of food and energy.²² As a result, population density also grew, and that of major European countries (France, Italy, Germany, England, and the Low Countries) in the mid-eighteenth century was about 40–60 persons per km², 100 times greater than that of the hunters and gatherers. Naturally, productive capacity varied greatly in different epochs as a function of technological and social evolution, a point easily demonstrated by comparing the agriculture of the Po Valley or the Low Countries with the fairly primitive methods used in some parts of the continent. Throughout the globe, innovation has allowed for the notable expansion of productivity per unit of energy invested.

It appears, for example, that productivity per hectare tripled in Teotihuacán (Mexico) between the third and second millennia BCE due to the introduction of new varieties of corn,²³ and in various zones of Europe during the modern era the ratio of agricultural production to seed increased thanks to new grains.²⁴

Nonetheless, success in mastering the environment has always been dependent upon the availability of energy. As Cipolla observed, “the fact that the main sources of energy other than man’s muscular work remained basically plants and animals must have set a limit to the possible expansion of the energy supply in any given agricultural society of the past. The limiting factor in this regard is ultimately the supply of land.”²⁵ In preindustrial Europe, populations seem to have approached with some frequency the limits allowed by the environment and available technology. These limits may be expressed by the per capita availability of energy and, again following Cipolla, must have been below 15,000 cal, or perhaps even 10,000 cal, per day (a level that the richest countries today exceed by a factor of 20 or 30), the majority of which were dedicated to nutrition and heating.²⁶

The environmental limits to demographic expansion were again shattered by the enormous increase in available energy that resulted from the industrial and technological revolution of the second half of the eighteenth century and the invention of efficient machines for the conversion of inanimate materials into energy. World production of coal increased 10-fold between 1820 and 1860 and again between 1860 and 1950. It has been calculated that worldwide primary energy consumption almost tripled between 1800 and 1900, and increased ninefold between 1900 and 2000, and that per capita consumption expanded fourfold during the past two centuries, moving from a state of penury to one of relative abundance.²⁷ The dependency of energy availability on land availability was again (and perhaps definitively) broken, and the principal obstacle to the numerical growth of population was removed. A synthesis of this complex development has been made by Earl Cook: hunters and gatherers needed some 5,000 cal per capita and per day; agriculturalists probably never exceeded a consumption level of 12,000 cal; and before the Industrial Revolution even the most developed and structured populations’ consumption remained below 26,000 cal. In the initial phase of the

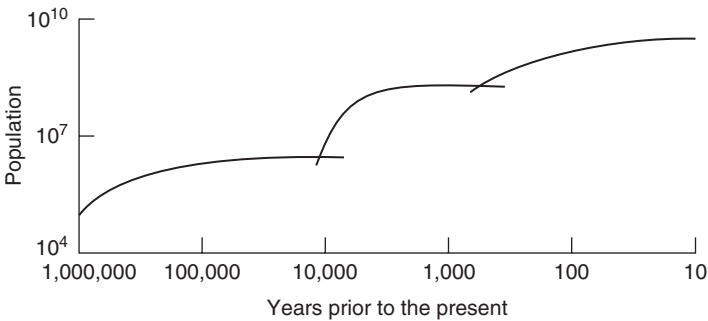


Figure 1.11 Cycles of demographic growth.

Industrial Revolution per capita consumption – derived mostly from fossil fuels – was of the order of 70,000 cal, while it exceeds 200,000 cal in some contemporary societies.²⁸

Figure 1.11, taken from Deevey,²⁹ describes schematically (on a double logarithmic scale and simplifying drastically the complexities of history) the evolution of population as a function of the three great technological–cultural phases described above: the hunter–gatherer (until the Paleolithic Age), the agricultural (from the Neolithic), and the industrial (since the Industrial Revolution). During these three phases (the last of which we are still in the middle of), the population has increased by increments that become progressively smaller with the passage of time, as the limits of growth are approached. This outline is simply the application of that concept, common to both animal biology and Malthusian demography, according to which the growth of a species (gnat, mouse, human, or elephant) in a restricted environment varies inversely with its density. This comes to pass because the available resources are considered fixed and so population growth creates its own checks. For the human species, of course, the environment, and so the available resources, has never been fixed but continually expands due to innovation. In the Deevey outline, demographic growth in the first long period of human history, which continued up until 10,000 years ago, was limited by the biomass available for nutrition and heating at a rate of several thousand calories per day per person. In the second phase, from the Neolithic to the Industrial Revolution, limits were

imposed on the availability of land and the limited energy was provided by plants, animals, water, and wind. In the present phase, the limits to growth are not so well-defined but may be connected to the adverse environmental effects of combined demographic and technological growth and the attendant cultural choices.

1.7 A Few Figures

On November 1, 2010, the People's Republic of China carried out its sixth census since the revolution and, with the help of 10 million carefully trained census personnel, counted 1.340 billion inhabitants. It was the largest social investigation ever undertaken. Until the middle of the twentieth century, there were still quite a few areas of the less-developed world for which there existed, at best, fragmentary and incomplete demographic estimates. In Western countries, the modern statistical era began in the nineteenth century, when the practice of taking censuses of the population at regular intervals, which began in some countries in the preceding century, became general. The 10.4 million persons counted in the Kingdom of Spain in the summer of 1787 by order of Charles III's prime minister, Floridablanca, and the 3.9 million counted in the United States in 1790 as instructed by the first article of the Constitution approved 3 years earlier in Philadelphia, are the first examples of modern censuses in large countries.³⁰ In previous centuries, there were, of course, head counts and estimates – often serving fiscal purposes – for limited areas and often of limited coverage. Included among the latter are the family lists from the Han to the Ching dynasties in China (covering a period of almost two millennia ending in the previous century).³¹ For the evaluation of these, the work of the statistician must be complemented by that of the historian, who is able to evaluate, integrate, and interpret the sources. In many parts of the world before this century, in Europe prior to the late Middle Ages or in China before the present era, one can only estimate population size on the basis of qualitative information – the existence or extension of cities, villages, or other settlements, the extension of cultivated land – or on the basis of calculations of the possible population

density in relation to the ecosystem, the level of technology, or social organization. The contributions of paleontologists, archaeologists, and anthropologists are all needed.

The data on world demographic growth, as presented in Table 1.1 and Table 1.3, are largely based on conjectures and inferences drawn from nonquantitative information. Table 1.1 presents a synthesis of

Table 1.3 Continental populations (400 BCE to 2050 CE, in million).

Year	Asia	Europe	Africa	America	Oceania	World
400 BCE	97	30	17	8	1	153
0	172	41	26	12	1	252
200	160	55	30	11	1	257
600	136	31	24	16	1	208
1000	154	41	39	18	1	253
1200	260	64	48	26	2	400
1340	240	88	80	32	2	442
1400	203	63	68	39	2	375
1500	247	82	87	42	3	461
1600	341	108	113	13	3	578
1700	437	121	107	12	3	680
1750	505	141	104	18	3	771
1800	638	188	102	24	2	954
1850	801	277	102	59	2	1,241
1900	921	404	138	165	6	1,634
1950	1,403	547	224	332	13	2,529
2000	3,714	726	814	841	31	6,127
2050	5,267	707	2,448	1,217	57	9,664
% rate of growth						
0–1750	0.06	0.07	0.08	0.02	0.06	0.06
1750–1950	0.51	0.68	0.38	1.46	0.73	0.59
1950–2000	1.95	0.57	2.58	1.86	1.74	1.78
2000–2050	0.70	–0.05	2.20	0.74	1.22	0.91

Sources: J. N. Biraben, “Essai sur L’évolution du Nombre des Hommes [Essay on the Evolution of the Population],” *Population* 34 (1979), p.16. For 1950, 2000 and 2050: United Nations, *World Population Prospects: The 2024 Revision* (New York, 2024).

these trends. The long-term rates of growth are, of course, an abstraction, as they imply a constant variation of demographic forces in each period, while in reality population evolves cyclically. Following Biraben's hypothesis, according to which human population prior to the High Paleolithic era (35,000–30,000 BCE) did not exceed several hundred thousand, growth during the 30,000 years leading up to the Neolithic era averaged less than 0.1 per 1,000 per year, an almost imperceptible level consistent with a doubling time of 8,000–9,000 years.³² In the 10,000 years prior to BCE, during which Neolithic civilization spread from the Near East and Upper Egypt, the rate increased to 0.4 per 1,000 (which implies a doubling in less than 2,000 years) and the population grew from several million to about 0.25 billion. This rate of increase, in spite of important cycles of growth and decline, was reinforced during the subsequent 17.5 centuries. The population tripled to about 0.75 billion on the eve of the Industrial Revolution (an overall rate of growth of 0.6 per 1,000). It was, however, the Industrial Revolution that initiated a period of decisive and sustained growth. During the following two centuries, the population increased about 10-fold with an annual growth rate of 6 per 1,000 (doubling time 118 years). This process of growth was the result of a rapid accumulation of resources, control of the environment, and mortality decline, and culminated in the second half of the twentieth century. In the four decades since 1950, the population has again doubled and the rate of growth has tripled to 18 per 1,000. In spite of signs that growth is slowing, the present momentum will almost certainly carry the world population to 9 billion by about the year 2037. The acceleration of the growth rate and shortening of the doubling time (which was expressed in thousands of years prior to the Industrial Revolution and is expressed in tens of years at present) give some indication of the speed with which the historical checks to population growth have been relaxed.

Table 1.1 responds to another question which, at first glance, appears to be simply a statistical curiosity. How many people have lived on the earth? The answer requires calculation of the total number of births in each of the periods indicated. Following the courageous hypotheses of Bourgeois-Pichat,³³ we can estimate the total

number of births from the origin of the human species to the year 2000 at 82 billion, of which 6 billion occurred since the 1950s, 3 billion less than that took place in the hundreds of thousands of years of human existence prior to the Neolithic era. In the year 2000, the 6 billion inhabitants of the globe represented 7.3 percent of the total number of human beings ever born. Taking a different approach, and keeping in mind that what we are today represents the accumulated experiences of our progenitors – selected, mediated, modified, and passed on to us – we can observe that 11 percent of these experiences were accumulated prior to the Neolithic era and more than 80 percent before 1750 and the industrial–technological revolution.

If we assign an estimated life expectancy at birth to the individuals in each epoch (these estimates are statistical only for the last period; for the preceding period, they are based on fragmentary evidence and before that, they are pure conjecture), we can then calculate the total number of years lived by each of these groups. Those born between 1950 and 2000 will have lived (at the end of their lives) about 334 billion years, almost twice the total number of years lived by all those born prior to the Neolithic era. The 420 billion years that will presumably be lived (during their whole lives) by those alive in 2000 represent a little less than one-fifth of all the years lived since the origin of the human race. Finally, with a rather gross estimate, we may say that humankind’s energy consumption, during the past 13 years or so, has been of the same order of magnitude as the total energy consumption from 0 CE to the onset of the Industrial Revolution.³⁴ These figures are not presented for their shock value but to demonstrate the extraordinary expansion of resources available to humanity today as compared to earlier agricultural societies.

Population, of course, did not grow continuously, but experienced cycles of growth and decline, the long-term aspects of which are summarized in Table 1.3 and Figure 1.11. Limiting ourselves to Europe, the tripling of the population between the BCE and the eighteenth century did not occur gradually, but was the result of successive waves of expansion and crisis: crisis during the late Roman Empire and the Justinian era as a result of barbarian invasions and disease; expansion in the twelfth and thirteenth centuries; crisis again as a

result of recurring and devastating bouts of the plague beginning in the mid-fourteenth century; a strong rallying from the mid-fifteenth century to the end of the sixteenth century; and crisis or stagnation until the beginning of the eighteenth century, when the forces of modern expansion came to the fore. Nor do these cycles run parallel in different areas, so that relative demographic weight changes with time: the European share of world population grew from 17.8 to 24.7 percent between 1500 and 1900, only to decline again to 11.9 percent in the year 2000. The entire American continent contained about 2 percent of the world's population at the beginning of the seventeenth century, while today the figure is 13.3 percent.

Notes

- 1 J. W. Goethe, *Italian Journey*, trans. W. H. Auden and E. Mayer (North Point Press, San Francisco, 1982), p. 46.
- 2 H. Cortés, *Cartas de relación* (Editorial Porrúa, Mexico, 1976), p. 62.
- 3 For the discussion that follows I have taken the lead provided by R. M. May and D. I. Rubinstein in their "Reproductive Strategies," in C. R. Austin and R. V. Short, eds., *Reproductive Fitness* (Cambridge University Press, London, 1984), pp. 1–23. See also R. V. Short, "Species Differences in Reproductive Mechanisms," in the same volume, pp. 24–61. An essay of broader scope is that of S. C. Stearns, "Life History Tactics: a Review of the Ideas," *Quarterly Review of Biology* 51 (1976). The relevance of r and K strategies to demography is supported by A. J. Coale in the first chapter of A. J. Coale and S. Cotts Watkins, eds., *The Decline of Fertility in Europe* (Princeton University Press, Princeton, NJ, 1986), p. 7.
- 4 May and Rubinstein, "Reproductive Strategies," p. 2.
- 5 May and Rubinstein, in "Reproductive Strategies." Note that for mammals there exists a close relationship between body weight and age of sexual maturity. As we shall see below, the rate of growth of a population can be derived from Lotka's equation, $r = \ln R_0 / T$, where T is the average length of generation and R_0 is the average number of daughters a generation of women have during their lifetime (net reproduction rate). It follows that r is reasonably sensitive to changes in T (closely linked to the age of sexual maturity) and less sensitive to changes in R_0 , as it is directly linked to $\ln R_0$. Changes in the value of T , then, from species to species, have a strong influence on the value of r .

- 6 F. MacFarlane Burnet, *Natural History of Infectious Diseases* (Cambridge University Press, London, 1962), p. 14.
- 7 May and Rubinstein, "Reproductive Strategies," p. 1.
- 8 I am indebted to Carlo Corsini for having supplied me with the following examples taken from family reconstructions for the diocese of Fiesole.
- 9 The discussion that follows is derived from H. Charbonneau, Réal Bates and Mario Boleda, *Naissance d'une Population. Les Français Établis au Canada au XVII^e Siècle* [*The Birth of a Population: The French Settlement in Canada in the XVIIth Century*] (Presses de la Université de Montréal, Montréal, 1987).
- 10 The average number of children per woman, or total fertility rate (*TFR*), is the sum of age-specific fertility rates for women between the minimum and maximum ages of reproduction, $f_x = B_x/P_xB_x$ is the number of births to a woman aged x , and P_x is the female population age x .
- 11 The discussion that follows owes a heavy debt to the work of J. Bongaarts and J. Menken, "The Supply of Children: A Critical Essay," in R. A. Bulatao and R. B. Lee, eds., *Determinants of Fertility in Developing Countries* (Academic Press, New York, 1983), vol. 1, pp. 27–60. The evaluation of the components of fertility is based on the assumption that all births are the products of stable unions (marriage), an hypothesis close to reality for many cultures and periods.
- 12 These various hypotheses fit into the Bongaarts and Menken model. In fact, the number of children (*TFR*, so ignoring mortality) is obtained by dividing the length of the reproductive period (age at the birth of the last child minus the average age at marriage) by the birth interval. In the model the age at marriage is made to vary between 15 and 27.5 years (22.5 in the standard model) and the average age at the birth of the last child varies between 38.5 and 41 (40 in the standard). For calculating the birth interval, the minimum, maximum, and standard values (in years) for the components are the infecund postpartum anovulatory period (0.25, 2.0, 1.0), the waiting period (0.4, 0.85, 0.6), and fetal mortality (0.1, 0.2, 0.15).
- 13 I shall make frequent reference to the life table, and so it will be useful at this point to briefly illustrate its workings, referring the reader to specialized publications for a more in-depth treatment. A life table describes the gradual extinction of a generation of newborns (or hypothetical cohort) with the passage of time. This cohort conventionally consists of 10^n individuals; let us use 1,000.

The values of l_x , where x represents age, describe the number of survivors of the initial 1,000 at each birthday up until the complete extinction of the generation. Another fundamental function of the life table is q_x (conventionally expressed per 1,000 or other power of 10),

which represents the probability that the survivors at birthday x will die before birthday $x + 1$. These probabilities can refer to periods longer than a year, and the prefixes 1, 4, and 5 (or other values) indicate the age intervals to which the probability refers. Another frequently used function is life expectancy, or e_x (where x again refers to a specific birthday), which indicates on average the number of years of life remaining to those who have survived to age x (l_x), given the mortality levels listed in the life table. “Life expectancy at birth” is expressed by e_0 . Here there is an apparent paradox: in life tables that reflect the high mortality of historical demographic regimes, life expectancy increases for several years after birth ($e_0 < e_1 < \dots e_5$, and even beyond). This is owing to the fact that in the first years of life large numbers of babies are eliminated who contribute little to the sum of years left to live for the generation and so lower the average value represented by life expectancy. Once this effect has ceased, after a few years, depending upon mortality levels, life expectancy begins its natural decline with age. Keep in mind, however, that in high-mortality regimes, e_{20} , for example, can be higher than e_0 .

- 14** Since the 1970s, the decline of mortality at very old ages (over 80) in low-mortality countries has accelerated (1–2 percent per year). If this trend were to continue, the proportion surviving to age 100 could become significant, and the hypothesis of the “rectangularization” of the survival curve would become unlikely, as the entire l_x curve would gradually shift to the right. See V. Kannisto, J. Lauritsen, A. R. Thatcher, and J. W. Vaupel, “Reductions in Mortality at Advanced Ages: Several Decades of Evidence from 27 Countries,” *Population and Development Review* 20:4 (1994). Also J. R. Wilmoth, “The Future of Human Longevity: a Demographer’s Perspective,” *Science* 280 (1998); J. Vaupel, “Biodemography of Human Ageing,” *Nature* 464 (2010).
- 15** This is theoretical because, while the survival of an individual beyond the reproductive period may not contribute directly to reproduction, it may nonetheless improve the children’s chances for survival.
- 16** The preceding discussion includes in a simplified form several fundamental demographic relationships, which may be useful to explain more fully. In a stable population (one subject to levels of mortality and fertility that are unchanging in time), the age structure and rate of growth are also fixed according to the following equation:

$$R_0 = e^{rT}$$

where R_0 is the net reproduction rate, or the number of daughters that each woman on average produces during the entire reproductive period. It may also be expressed as:

$$R_0 = \sum f_x l_x$$

where f_x is the age-specific fertility rate, or the number of daughters born per woman at age x , and l_x is a survivorship function (the ratio between the survivors at age x and the size of the generation at birth). Returning to the first equation, T is the average length of generation, which is fairly well approximated by the average age of childbearing, and varies for human populations within a narrow interval (27–33 years); r is the rate of growth for a stable population. In this ideal stable population, the rate of growth r varies directly with R_0 , the number of daughters per woman, and inversely with T . It should be added that the net reproduction rate bears a close relationship to the gross reproduction rate R , which is the sum of the f_x and describes the number of daughters per woman in the absence of mortality. The relationship between R_0 and r is well approximated by the equation $R_0 = Rl_a$, where l_a is the probability of survival from birth to the average age of childbearing a . The initial equation may be rewritten as:

$$Rl_a = e^{rT}$$

If we imagine T is constant (in fact it varies little), then the rate of growth r can be expressed as a function of l_a , an index of mortality, and R , an index of fertility. It can be demonstrated that l_a is very nearly equal to the values calculated in Figure 1.6 for the percentage of the reproductive life utilized. Furthermore, l_a is strongly correlated with e_0 , or life expectancy at birth, so r may be expressed as a function of R and e_0 . Finally, there is a close relationship between R and TFR (average number of children per woman in the absence of mortality): one simply multiplies R by 2.06 (a constant representing the ratio between total births and female births) to obtain TFR . In Figure 1.3, r is expressed as a function of TFR and e_0 , using a value of T equal to 29 years.

- 17 See note 16.
- 18 It may be useful to recall a mnemonic device for the calculation of population-doubling time. These can be approximated by dividing 70 by the annual growth rate (expressed as a percentage): a growth rate of 1 percent implies a doubling time of 70 years, 2 percent of 35 years, 3 percent of 23 years. Similarly, if the growth rate is negative, the population-halving time is obtained by the same method: if the population is declining by 1 percent per year, it will halve in 70 years, if by 2 percent in 35 years, and so on.
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- 32 The estimates in Tables 1.2 and 1.3 are taken from J. N. Biraben, “Essai sur l’Évolution du Nombre des Hommes [Essay on the Evolution of the Population],” *Population* 34 (1979), pp. 13–25. See also J. D. Durand, “Historical Estimates of World Population,” *Population and Development Review* 3 (1977); A. J. Coale, “The History of Human Population,” *Scientific American* (September 1974), pp. 40–51.
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34 IEA estimates in 9,301 Mtoe (million tons of oil equivalent) the total energy final consumption in 2013, corresponding to a per capita consumption of 1.295 toe. In a preindustrial society, we have assumed (with Cipolla) per capita daily consumption of 10,000 kcal, or 0.1895 toe per capita per annum. Today's world population, therefore, consumes (per capita) 6.8 times the (per capita) consumption of preindustrial populations. In the United States, per capita consumption is about 7 toe per capita, 20 or 30 times higher than in the poorest countries of sub-Saharan Africa. In the 611 billion years lived between 0 and 1750 CE (see Table 1.1), total consumption must have been $0.1895 \times 611 = 115.8$ billion toe. An equal number of toe has been consumed in the 89.4 billion years lived by world population in the 13-year period from 2003 to 2015.

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