A PRIMER ON POPULATION DYNAMICS AND ZPG

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INTRODUCTION

This article provides a non-mathematical primer on the principles of population dynamics and a background on the prospects of the world population achieving Zero Population Growth (ZPG). For a comprehensive description and the mathematics of population dynamics, I recommend the book *Applied Mathematical Demography* by Keyfitz & Caswell, 2005.

Population dynamics is the study of changes in population size by tracking births, deaths, and net migration. The size of the world population in 10,000 BC is estimated to have been 2.4 million people (Hyde, 2019). As shown in Figure 1, growth in the size of our human population was very slow for many thousands of years. It is only over recent centuries that growth has accelerated.

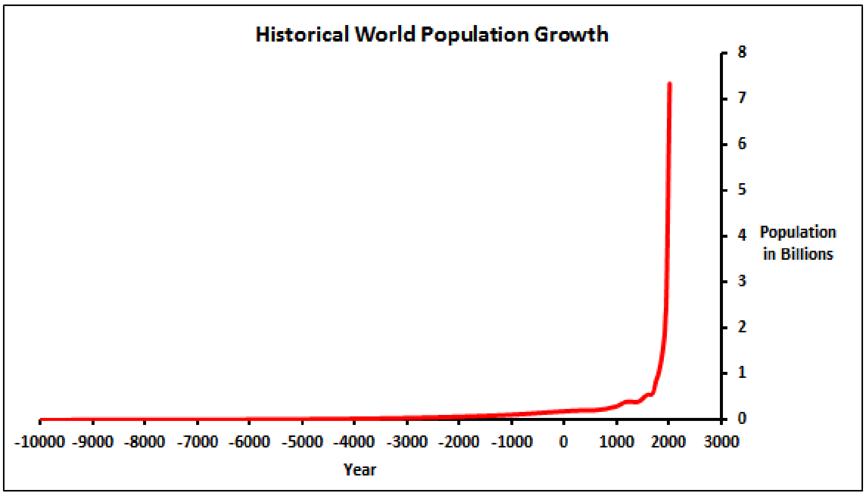


Figure 1: History of World Population Growth (Data: Hyde, 2019)

The number of years that it takes for an exponentially growing population to double in size is approximately 70 divided by the annual growth rate as a percentage. For example, a population growing by 2.0% each year would take 35 years to double in size. Table 1 below shows it has taken almost 12,000 years and 11 doublings in size for our human population to grow from 2.4 million people in 10,000 BC to 5.0 billion people in 1986. If our human population of 12,000 years ago had doubled in size at a constant annual growth rate of 2.0% per year, a rate that was surpassed in the 1960s, then it would have taken 385 years (35 years x 11 doublings) for the world population to increase to 5 billion people.

As shown in Table 1, the average annual growth rate of our human population between 10,000 BC to 1000 AD was very slow at 0.04% per year. The average annual growth rate increased significantly between 1000 AD to 1700 AD (0.10% per year) and then started to progressively accelerate from 1700 to 1850 during the start of the industrial revolution (0.50% per year), from 1850 to 1950 during large scale mining of coal and drilling of oil (0.69% per year), and then especially from the 1950s through to the 1960s during the green agricultural revolution (1.89% per year).

Table 1: Historical Human Population Doubling Times (Data: Hyde 2019)

Date	Population (Number)	Doubling Time (Years)	Average Annual Growth Rate (%)
10000 BC	2,430,000		
8148 BC	4,860,000	1,852	0.04
6387 BC	9,720,000	1,761	0.04
4821 BC	19,440,000	1,566	0.05
3305 BC	38,880,000	1,516	0.05
1834 BC	77,760,000	1,471	0.05
432 BC	155,520,000	1,402	0.05
1033 AD	311,040,000	1,465	0.05
1706 AD	622,080,000	673	0.10
1847 AD	1,244,160,000	141	0.50
1949 AD	2,488,320,000	102	0.69
1986 AD	4,976,640,000	37	1.89

During the 20th century our world population doubled within one lifetime and there are now strong signals that our world population has exceeded the carrying capacity of our planet Earth (Cohen, 1995). The per capita rate of consumption and the impact of using resources can be reduced more so than that which is current by increasing the efficiency of using resources and by greater use of recycling. However, there are physical and thermodynamic limits to the possible extent of increases in efficiency and recycling. Both efficiency of use and recycling are subject to diminishing returns.

Regardless of the per capita rate of consumption of resources, a larger human population will consume more resources than a smaller population. Continued growth in human populations exacerbates the impact of climate change and accelerates the peaking of fossil fuels and mining of minerals at the very same time that fossil fuels are needed to enable a transition to renewable energy. Continued increases in population during a transition from fossil fuels to renewable energy can but only result in a Sisyphus like undermining of efforts for a smooth transition.

In 1972 the Club of Rome published the book *The Limits to Growth* which advocated ZPG as soon as possible (Meadows et al., 1972)). The world population back then was 3.8 billion people. By January 2019 the world population had grown to 7.7 billion people (United Nations, 2019) and the world population continues to grow, continues to consume more fossil fuels, and continues to add more CO_2 and methane to the atmosphere. Partial good news is that the annual growth rate of the world population peaked at 2.11% in 1971 and since 1971 the world population has continued to increase in size, but at a declining growth rate.

CRUDE BIRTH AND DEATH RATES

The crude birth rate (b) is the ratio of births over one year per 1,000 people within a population. A high present-day crude birth rate is in the order of 50 births per 1,000 people per year. Pre-historic crude birth rates are thought to have been around 40 to 50 births per 1,000 people per year. The crude death rate (d) is the total deaths at all ages per 1,000 people per year. There is no upper limit on the crude death rate as war, disease, and pestilence take their toll. However, because we are all mortal, there is a lower limit. With our present-day way of life with sound nutrition and medical care, a low crude death rate is in the order of 5 deaths per 1,000 people per year. Figure 2 below shows the world crude birth and death rates from 1960 to 2016.

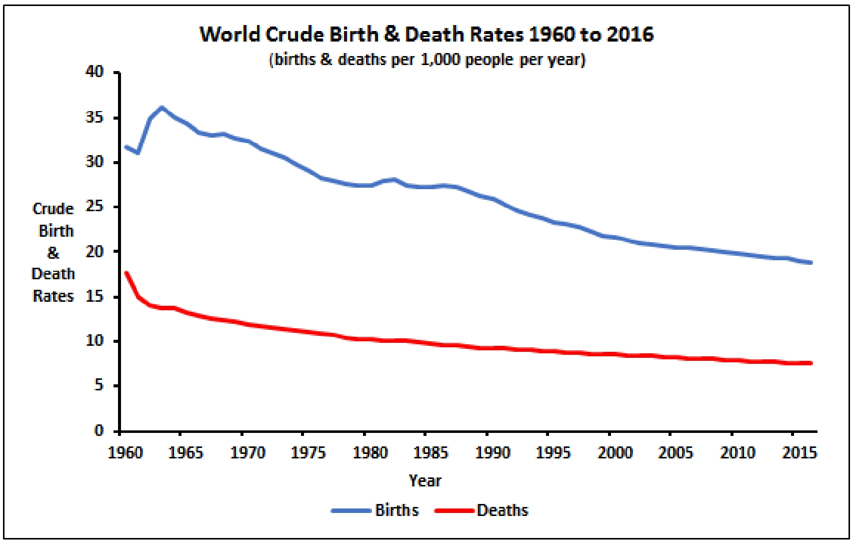


Figure 2: World Crude Birth & Death Rates 1960 to 2016 (Data: United Nations 2019)

With improvements in medical care and nutrition there was a simultaneous sharp decline in the crude death rate and sharp increase in the crude birth rate until 1965 which resulted in a population boom. From 1965 onwards both the crude birth and death rates declined in tandem with the crude birth rate declining more rapidly.

CAUSES OF DEATHS

There is but only one cause of births which is conception, but many causes of deaths which include immediate death due to injury by accident etc. or underlying causes which include the following: communicable diseases; maternal, prenatal and nutrition conditions; infectious and parasitic diseases; respiratory infections; and nutritional deficiencies such as underweight and stunting.

Table 2 shows statistics in 1990 and 2016 on three types of underlying causes of deaths as a proportion of the total of these deaths within three groups of countries.

Table 2: Underlying Causes of Deaths in Countries by Socio-Demographic Index (SDI) 1990 & 2016 (Data: Our World in Data 2019)

Countries	Year	Deaths due to non-communicable diseases (% of total deaths)	Deaths due to Communicable, maternal, neonatal, and nutritional diseases (% of total death)	Deaths due to Injuries (% of total deaths)
High SDI	1990	87.9	5.2	6.9
High SDI	2016	89.3	5.1	5.6
Middle SDI	1990	64.0	24.3	11.7
Middle SDI	2016	80.4	10.5	9.1
Low SDI	1990	24.7	68.1	7.2
Low SDI	2016	38.4	53.1	8.6

The countries have been grouped using the socio-demographic index (SDI) which is a summary measure of a country's development based on average income per person, educational attainment, and fertility. Total fertility, the average number of children per family is addressed in more detail in a section below.

The proportion of underlying deaths due to injuries in the high, middle, and low SDI countries were of a similar magnitude in 1990 ranging from 6.9% to 11.7% and the shifts in the proportion of these deaths from 1990 to 2016 were minor compared to the other underlying causes of deaths.

The significant difference in the underlying causes of deaths between the SDI group of countries in 1990 was due to communicable, maternal, neonatal, and nutritional diseases. This proportion of deaths was 5.2% in the high SDI countries compared to 24.3% and 68.1% in middle and low SDI countries respectively. The significant difference was due to the difference in the level of medical care and nutrition in each SDI group of countries. There was little change in this proportion of deaths from 1990 to 2016 in the high SDI countries (5.2% to 5.1%, a reduction to 98% of the previous proportion). The reduction in this proportion of deaths was significant in the middle SDI countries (24.3% to 10.5%) and less so in the low SDI countries (68.1% to 53.1%). The proportion of underlying causes of deaths due to non-communicable diseases subsequently increased in all SDI countries.

The high proportion of deaths due to communicable, maternal, neonatal, and nutritional diseases in the low SDI countries in 2016 is of major concern, especially when this category of deaths is preventable with better medical care and nutrition. Lack of sufficient medical care and nutrition reflects the inequity in income and educational attainment between countries.

INFANT MORTALITY RATE

The infant mortality rate is the number of infants dying before reaching one year of age per 1,000 female live births in a given year. Complete annual series of Infant mortality statistics are available for most countries from 1960 to 2017. The infant mortality rates for a selection of countries are shown in Figure 3.

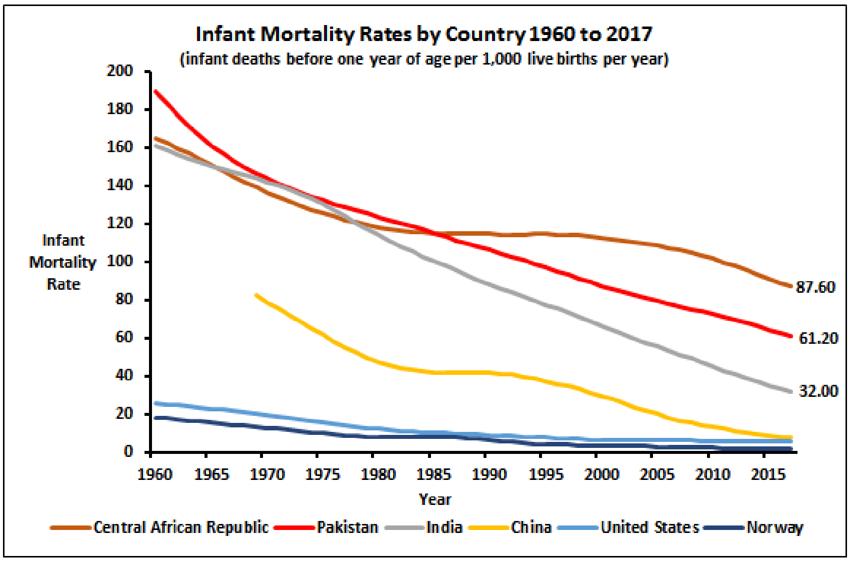


Figure 3: Infant Mortality Rates by Country 1960 to 2017 (Data: United Nations 2019)

The selection of countries in Figure 3 is indicative of the typical extreme differences in infant mortality rates between all countries in 1960 and the substantial closing of the gaps by 2017. For example, in 1960 infant mortality rates for Pakistan and Norway were 189.8 and 18.4 units respectively. By 2017 both previous infant mortality rates had declined to 61.2 and 2.1 units respectively. The initial gap of 171.4 units had closed to a gap of 59.1 units, a reduction to 34.4% of the previous gap.

Of the selection of countries in Figure 3, the largest decline in infant mortality rates occurred in the Central African Republic, Pakistan, India, and China. These countries also had the highest infant mortality rates in 1960. India had the largest recorded decline in infant mortality rates from 161.4 units in 1960 to 32.0 units in 2017, a decline to 19.8% of the previous 1960 level. Statistics for China are not available prior to 1969 for comparison. The United States and Norway had infant mortality rates of 25.9 and 18.4 units in 1960 which respectively declined to 5.7 and 2.1 units by 2017.

The low infant mortality rates of the higher income countries of the United States and Norway and the much higher infant mortality rates of the lower income countries of Central African Republic, Pakistan, and India as shown in Figure 3 are representative of all higher and lower income countries.

Figure 4 shows the infant mortality rates from 1990 to 2017 for all countries separated into low, middle, and high-income groups as classified by the United Nations. This classification is based on a country's level of development as measured by per capita gross national income (GNI). To maintain compatibility with similar classifications used elsewhere, the threshold levels of GNI per capita are those established by the United Nations. Countries with less than $1,035 GNI per capita are classified as low-income countries, those with between $1,036 $12,615 as middle-income countries, and those with incomes of more than $12,615 as high-income countries.

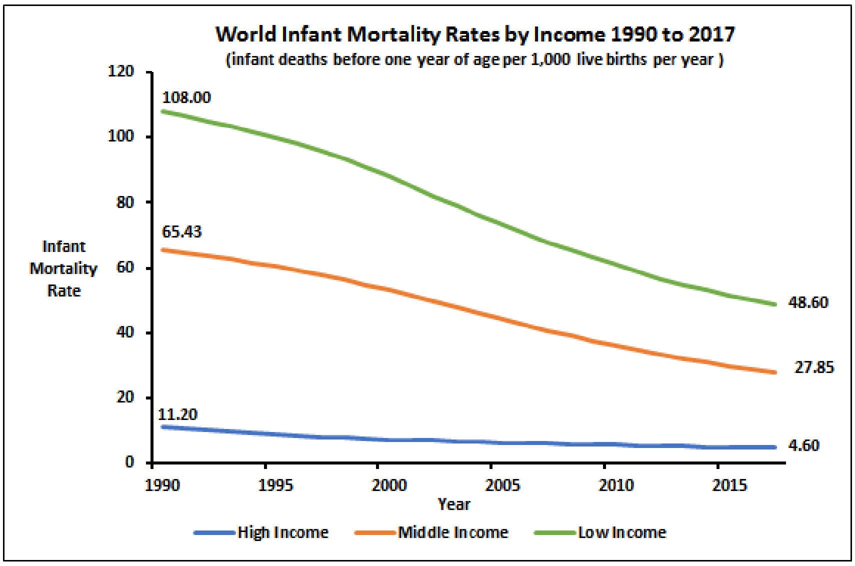


Figure 4: World Infant Mortality Rates by Income 1990 to 2017 (Data: United Nations 2019)

World infant mortality has declined substantially in middle-income and low-income countries since 1960. Populations of countries with high infant mortality rates tend to grow faster than those countries with low infant mortality rates.

GROWTH RATE

Population growth is an input-output process just like capital investment and depreciation in our economic system. Population growth in any one year is the result of the crude birth rate being higher than the crude death rate. The growth rate (r), the crude birth rate less the crude death rate (b-d), describes the increase of births over deaths per 1,000 people per year within a population. A growth rate of 10 births over deaths per 1,000 people per year is the same as a 1.0% annual increase in the natural population with no migration. Populations can also grow due to positive net migration – the numbers of immigrants entering the country in any one year exceed the number of emigrants who leave the country.

Pre-agricultural society is an example of low growth rate populations. The average high crude death rate would have been only fractionally less than the average high crude birth. On average, only slightly more than two children per women would have survived to a mature reproduction age.

Crude birth and death rates in a human population can and will fluctuate from year to year. A necessary condition of Zero Population Growth (ZPG) is that the average crude birth rate from generation to generation equals the average crude death rate. If the average crude death rate were to remain stable at 5 deaths per

1,000 population per year, then ZPG would occur when the average crude birth rate is also 5 births per 1,000 population per year. In a population of 1 million people, this would be 5,000 deaths replaced by 5,000 births over one year. A ZPG population can be maintained by low average crude birth and death rates and also by high average birth and death rates which was very nearly the case from 10,000 BC to 1000 AD when the growth rate of 0.04% was very low with a subsequent population doubling time of about 1,750 years.

When a population is growing rapidly, it is more illuminating to focus on changes in the growth rate rather than the population level as shown in Figure 5.

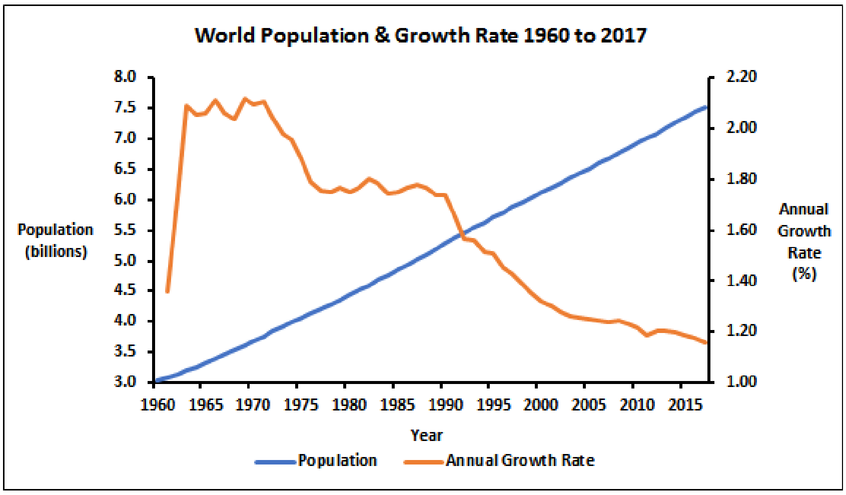


Figure 5: World Population & Growth Rate 1960 to 2017 (Data: United Nations 2019)

The world population grew from 3.0 billion people in 1960 to 7.5 billion people in 2017. From 1960 until 2017 the growth rate had been almost linear rather than exponential. The reason why is provided by examining the change in the growth rate. The growth rate increased rapidly prior to 1960 to a high of 2.11% in 1971 when almost 78 million people in that year were added to the world population. The world population growth rate then declined monotonically to 1.16% in 2017 except for a period between 1975 to 1990 when the growth rate fluctuated up and down.

Figure 6a and Figure 6b show the population growth and growth rates respectively from 1960 to 2017 for countries grouped by income.

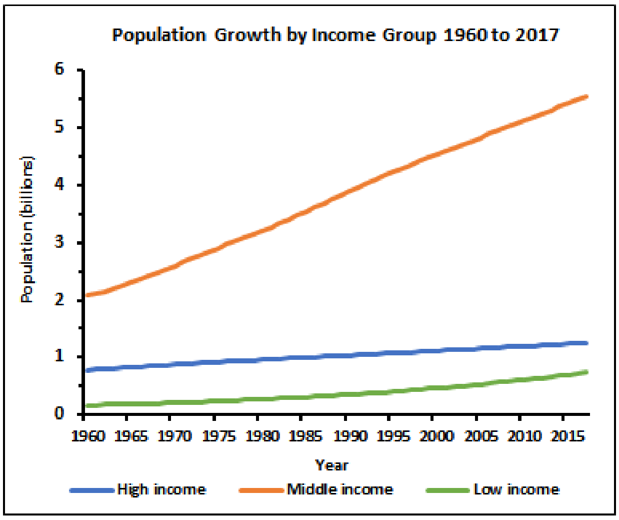


Figure 6a: Population Growth by Income (Data: United Nations 2019)

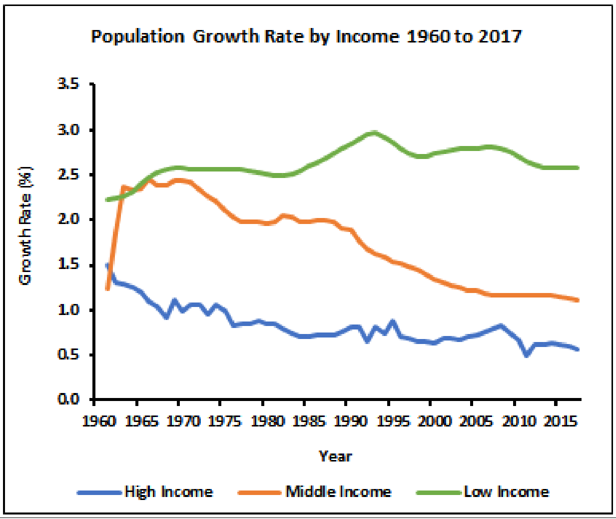


Figure 6b: Population Growth Rate by Income (Data: United Nations 2019)

The size of the populations in the middle-income countries in 1960 and subsequent annual growth rates have dominated growth in the world population. Although the size of the populations in all three income groups have increased monotonically from 1960 to 1970, growth rates in the high-income and middle-income countries have slowed down substantially over the same time frame from 1.28% and 2.37% in 1963 to 0.56% and 1.11% in 2017 respectively. In contrast, the growth rate of low-income countries was 2.26% in 1963, increased to a peak of 2.96% in 1993 and then fluctuated down to 2.58% in 2017.

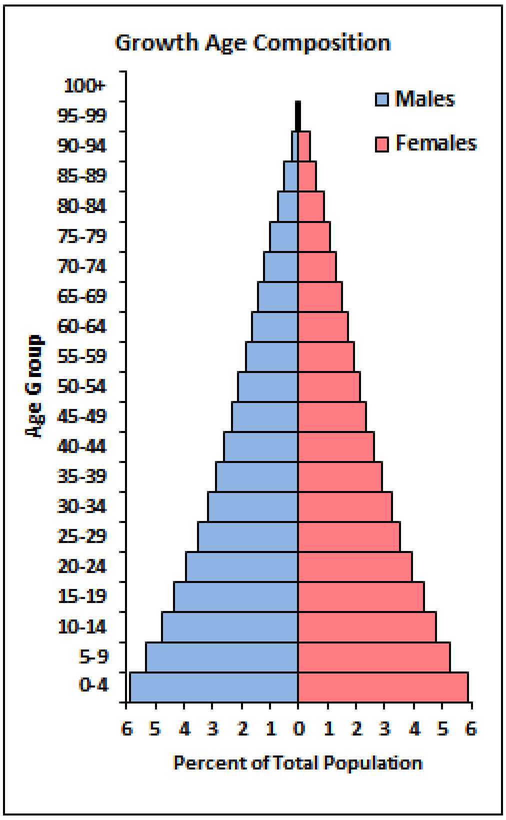
There are substantial differences in the growth rates of countries within income groups and especially in the low-income group of countries. For example, the growth rate of Uganda in 1963 was 3.42% which slowed down to 3.31% in 2017.

AGE COMPOSITION

When forecasting the future size of a population, the changing age composition of the population must be considered. Figure 7 below shows the age compositions of two idealised populations in a stack of cohorts by age: one that that has undergone continuous rapid annual growth and one that has achieved stationary and steady state ZPG. The rapid growth population has been set to grow exponentially at the constant rate of 2.0% per year for a period of more than 100 years and the fertility and mortality of the population during this period has been set to remain static.

The mortality of the ZPG population is based on the mortality of the New Zealand population in 2014-2016 where the average life expectancy of males and females were 80 and 83 years respectively (Statistics NZ, 2016). This mortality has been set to remain constant for over 100 years in the ZPG population. For the sake of comparison, the mortality of the continuous rapid growth population has also been set to the same mortality. In practice, rapid growth populations tend to have high crude death rates with a subsequent low average life expectancy. For example, the crude death rate of Nigerians in 1960 was 26.4 deaths per 1,000 people per year with a corresponding average life expectancy of 37.0 years for males and females combined (United Nations, 2019). These statistics improved to 12.5 deaths per 1,000 people per year and an average life expectancy of 53.4 years by 2016. Average life expectancy is addressed in more detail in a section below.

The rapid growth population has a triangular spear shape profile which is typical of a country with a high crude birth rate. As females from a birth cohort rise up the stack of age cohorts into the child-bearing age rank of cohorts (ages 15 to 44), each subsequent rank of child-bearing cohorts give birth to more children than previous ranks. More children are born each year and the population continues to grow exponentially.



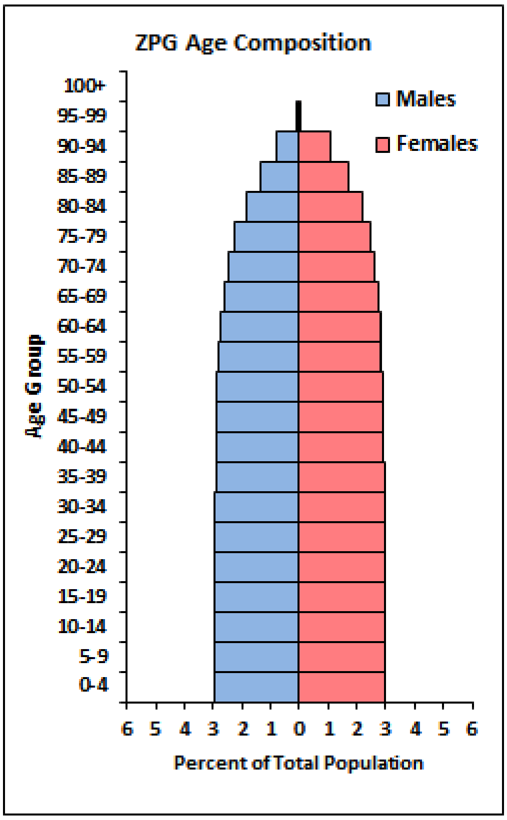


Figure 7: Age Composition in a Growth & ZPG Population

The profile of the rapid growth stack of cohorts by age composition is commonly referred to as a pyramid. This expression is a misnomer if applied to the ZPG population. The ZPG population has a tapering cylindrical shape profile which is typical of a country with a low crude birth rate. The tapering is due to progressive mortality with age resulting in a larger proportion of departures (deaths) from each older cohort. Mortality becomes more absolute at the higher age cohorts, hence closure of the tapering at the age of 100 with only a few in the population surviving beyond 100 years.

A transition of the world population to a ZPG population can be described as taking place over 4 stages.

> In stage 1 both crude birth and death rates are high with a slightly higher crude birth rate resulting in a very slow growth rate.
>
> In stage 2 the health of the world population starts to improve and mortality declines. Fertility remains at the same high level, so growth in the population starts to increase rapidly.
>
> In stage 3 social changes take place and families choose to have fewer children. Effective contraception becomes available and women become emancipated taking charge of their own reproduction. More women enter the work force rather than staying at home to raise a large family and total fertility subsequently declines. The growth rate of the population slows down, but the population continues to grow due to population momentum which is addressed in more detail in a section below
>
> In stage 4 the age composition of the population eventually stabilises, by which time the population has reached ZPG.

In a ZPG population there are more adults over the age of 65 than children under the age of 15. In a transition from a growth population to a ZPG population, the ratio of the number of dependents under the age of 15 and over the age of 65 to the number of working age from 15 to 64 changes. This change in ratio is described in more detail in a section below.

In an idealised text book description of ZPG population, the fertility and mortality of a population are both static and the age composition of the population remains stationary without change. Fertility and mortality fluctuate from year to year in practice, but from generation to generation the size of a ZPG population would remain more or less unchanged. In a ZPG population, the size of any cohort would be smaller than a younger cohort. This would not be the case when the fertility and/or mortality of a population undergo major changes or when a population transitions from growth to ZPG.

An example of a major change in fertility is the population of China. In 1978, Chinese women had 2.94 children on average compared to the world average of 3.85 children (United Nations, 2019). In 1979 China adopted a one child per family policy. This policy was discontinued in 2016 when China adopted a two-child policy. By 2015 Chinese woman had 1.62 children on average compared to the world average of 2.45 children.

The one-child policy had a dramatic and lasting impact on the age composition of the Chinese population as shown in Figure 8 below.

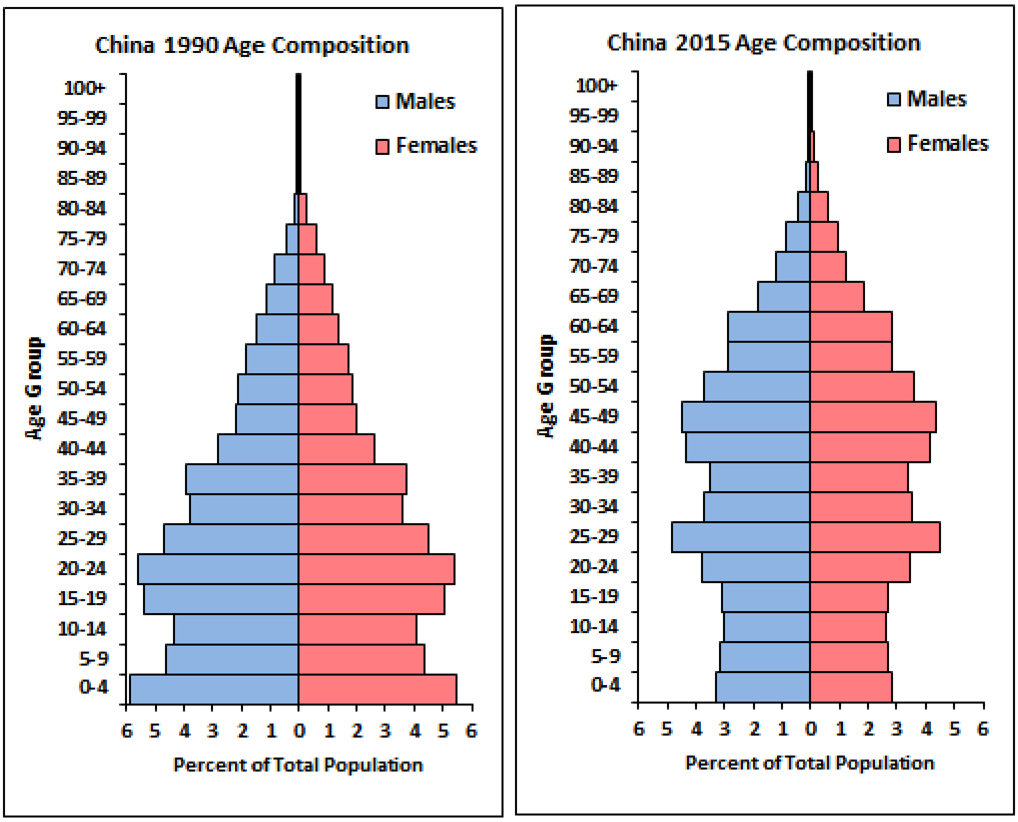


Figure 8: Age Composition of China in 1990 & 2015 (Data: United Nations 2019)

In the mid-1980s the one-child policy was modified to allow families in rural areas to have two children if the first child was female. There were also other exceptions to the one-child policy. Between 1979 to 2015 about 50% of Chinese families had two children rather than only one child or no children. The impact of the one-child policy can be seen in the reductions in births of the 0-4 age cohort moving up the age composition stack of cohorts over time.

POPULATION MOMENTUM

In a transition from a growth to a ZPG population, there is a momentum of growth in the population. The age composition of the population will change as the crude birth rate declines to match and equal the crude death rate. During the decline in crude birth rates, the crude death rate of low-income countries would also decline with better nutrition and medical care thus delaying crude birth rates from matching crude death rates. If crude births rates were to equal crude death rates and maintained, then the population would continue to grow due to a bulge of females moving up the age composition stack of cohorts into the child-bearing rank of cohorts between the ages of 15 to 44. The growth rate would slowly decline towards zero as females from the last and final growth cohort move up through the age composition stack of cohorts from the 0 to 4 cohort to the 45 to 49 cohort beyond the child-bearing age rank of cohorts. During this period the population would continue to grow, albeit progressively more slowly.

In 1971, demographer Nathan Keyfitz calculated that if the less developed countries with high birth rates were to achieve a replacement fertility rate overnight, then their populations would continue to increase until they stabilised at about 1.6 times their then present size. If a replacement fertility rate took 30 years to achieve, then their final populations would be 2.5 times their then present size (Keyfitz, 1971).

TOTAL FERTILITY

The crude birth rate does not compensate for changes in age composition. A better indicator of birth trends is the general fertility rate, the number of births per 1,000 women per year between the ages of 15 and 44. A more meaningful fertility indicator is the average completed family size or total fertility. At the replacement fertility level, each family on average would comprise of 2.11 children. The extra 0.11 child on average compensates for those children who do not survive to reproduction age and for those women who do not have children by virtue of choice or infertility.

Figure 9 shows the total fertility for the world population from 1960 to 2016. Once again, the annual rate of change in total fertility is illuminating.

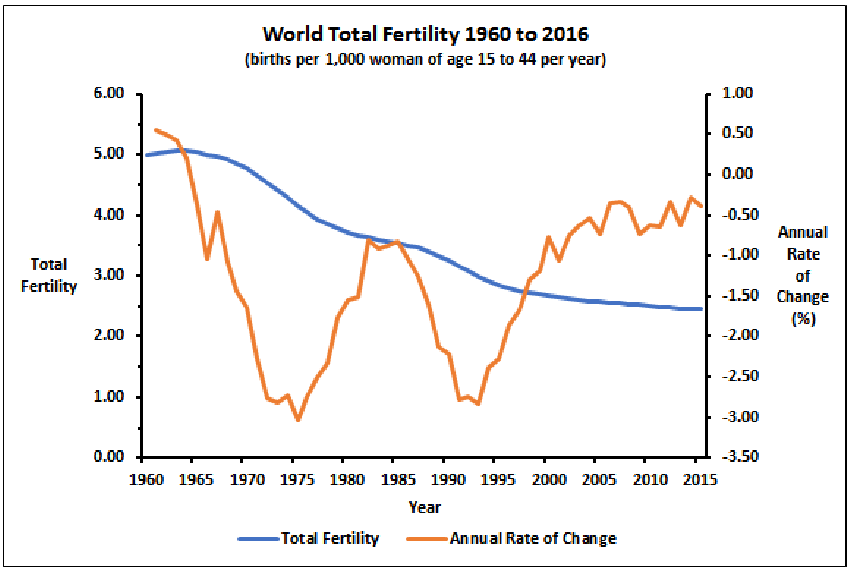


Figure 9: World Total Fertility 1960 to 2016 (Data: United Nations 2019)

World total fertility increased to a maximum of 5.07 children per family in 1964 and then declined monotonically to 2.44 children per family in 2016. The rate of decline in total fertility increased to a level of -3.03% per year in 1975, slowed down to a level of -0.82% per year in 1985, increased again to a level of -2.84% per year in 1993, and then slowed down again to a level of -0.39% per year in 2016. Apart from some fluctuations, the largest improvements in reductions in total fertility occurred between 1964 and 1975 and then between 1985 and 1993.

The slowdown in the rate of decline in total fertility since 1993 is not good news. The world population was 7.7 billion people in January 2019 (United Nations, 2019). If the world population were to continue to grow exponentially at the same annual growth rate of 1.07% from 2018 to 2019, then the world population would double in size within 66 years to 15.4 billion people in the year 2087.

Table 3 compares the size, proportion, and increase in the world population by income.

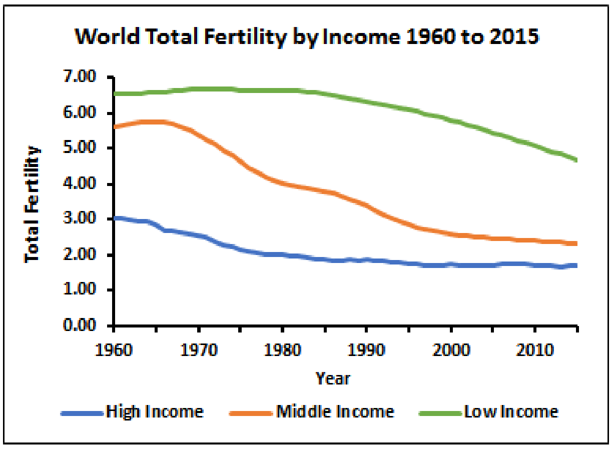
Table 3: World Population by United Nations Income Classification (Data: United Nations, 2019)

Income Group	1960		2017		1960 to 2017
	Population	% of World Population	Population	% of World Population	Increase in Size
high-income Countries	780,501,923	25.7	1,249,066,228	16.6	1.60 X
middle-income Countries	2,085,155,624	68.8	5,548,845,363	73.7	2.66 X
low-income Countries	166,602,848	5.5	732,448,558	9.7	4.39 X
World	3,032,160,395	100.0	7,530,360,149	100.0	2.48 X

In 1960 the high-income countries formed 25.7% of the world population. By 2017 these countries formed 16.6% of the world population due to the low annual growth rate of this income group. The middle-income countries formed 68.8% of the world population in 1960 and by 2017 formed a slightly larger proportion of 73.7%. The low-income countries formed only 5.5% of the world population in 1960 and almost doubled that proportion to 9.7% by 2017 due to a rapid annual growth rate.

Between 1960 and 2017 the high-income, middle-income, and low-income countries have respectively added 469 million, 3,464 million, and 566 million people to the world population. Emigration from one income group of countries to another conceals the true extent of the above statistics. Total fertility in each income group of countries better signals the source of population growth.

Figure 10 compares the total fertility and its annual rate of change from 1960 to 2015 for the above income groups.



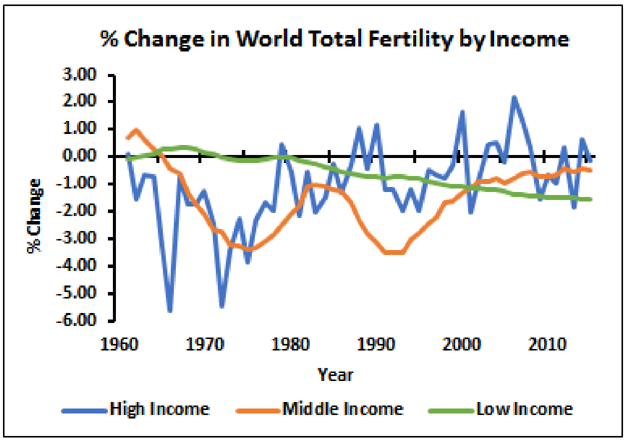


Figure 10: World Total Fertility by Income 1960 to 2015 (Data: United Nations 2019)

Total fertility tends to drop with prosperity. There are many reasons why, including low Infant mortality due to better medical care thus less reason to over reproduce as insurance towards being taken care of in old age, better nutrition, and access to medicine to combat life-threatening disease. The trend for nuclear families in high-income countries with both parents working during child rearing years also encourages smaller families. Total fertility also drops with education on family planning and access to contraceptives.

Global statistics on the prevalence of contraception are limited. Table 4 shows the United Nations Population Division statistics on the percentage of women who are practicing, or whose sexual partners are practicing, any form of contraception. The statistics are usually measured for women ages 15-49 who are married or in union.

Table 4: Contraception Prevalence in High-income, Middle-income, & Low-income Countries
(Data: United Nations 2019)

Income Group	Contraception Prevalence (%)		
	1990	2000	2014
High-income	70.05	69.99	67.27
Middle-income	58.66	61.63	65.09
Low-income	16.75	24.10	34.18

Use of contraception in the low-income countries has increased substantially from 1990 to 2014 (16.8% to 34.2%), but by 2014 was almost half of that in the high-income and middle-income countries. The reasons why include cultural lack of emancipation within some countries, lack of education on family planning, and lack of access to contraceptives.

Total fertility in the high-income countries averaged 3.04 children per family in 1960 and declined to 1.68 children per family by 2015. Total fertility in the high-income countries has been below replacement level of 2.11 children per family since 1976. Population growth, if any, in high-income countries since 1971 would be due to population momentum and positive net migration.

The rate of decline in total fertility in the high-income countries is of no great concern with regards to the prospects of achieving global ZPG, even though there have been spikes of increases in total fertility. The natural populations of these countries, excluding migration, have already achieved the primary requirement of ZPG that total births within each country should not exceed total deaths. There is a caution here though. Consistent crude birth rates well below that of crude death rates can result in potential undesirable changes in the age dependency ratio which is addressed in more detail in a section below.

Total fertility in the middle-income countries averaged 5.62 children in 1960 and declined to 2.33 children per family by 2015. The rate of decline in total fertility of the middle-income countries closely parallels that of the world population. As early as 1960 this group of countries already formed the largest proportion (68.8%) of the world population thus dominating the slowdown in the decline of the world total fertility since 1993. The rate of decline in total mortality in the middle-income countries slowed down to a rate of change of -0.46% by 2016.

Total fertility in the low-income countries averaged 6.57 children per family in 1960 and declined to 4.63 children per family by 2015. Although this change towards a lower total fertility has been less dramatic than that of the high-income and middle-income countries, the rate of decline has consistently improved to a level of -1.54% per year by 2015, a rate of change that exceeds that of the middle-income countries in 2015.

In 2017 the world population was 7.53 billion and the populations of the high-income, middle-income, and low-income countries were 1.25 billion, 5.55 billion, and 0.73 billion respectively (United Nations, 2019). The population of the middle-income countries was 7.60 time larger than that of the low-income countries. Consider the scenario where there is no migration between different income groups of countries and the natural populations of the high-income, middle-income, and low-income countries continue to grow unabated at their respective 2017 annual rates 0.56%, 1.11% and 2.58% (United Nations, 2019).

Figure 11a shows the populations of the middle-income and low-income countries continuing to grow in size until they are the same size of 26 billion during the year 2157. Figure 11b shows growth in the additions to the world population of 7.53 billion people since 2017 contributed by the middle-income and low-income countries.

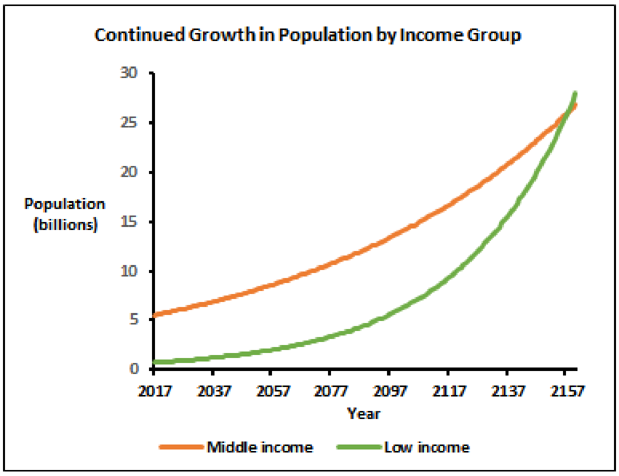


Figure 11a: Growth in Population (Data: United Nations 2019)

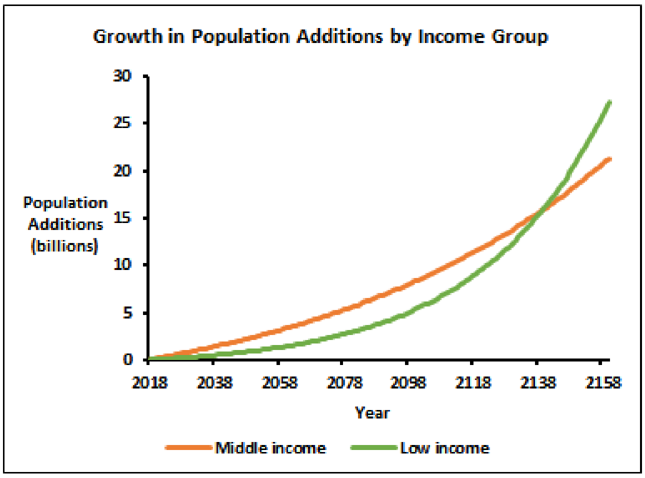


Figure 11b: Growth in Population Additions (Data: United Nations 2019)

Additions of population since 2017 by the middle-income countries exceed that of the low-income countries until the year 2140 during which year the additions of populations in both income group of countries total 16 billion people. The population of the high-income countries would increase from 1.25 billion to 2.48 billion people by 2140, an increase of 1.23 billion. In 2140 the world population would approach 41 billion people.

Irrespective of whether the above scenario is realistic or not, the scenario demonstrates that continued growth in the population of the middle-income countries will dominate future growth in the world population before the year 2100.

LIFE TABLES & LIFE EXPECTANCY

Average life expectancy at birth is the average number of years that a cohort of new-born infants would live if prevailing patterns of mortality at the time of birth were to stay the same throughout life. The average life expectancy at birth and remaining average life expectancies at each age are estimated using a life table which is based on age-specific crude death rates per 1,000 people of the same age. A typical abridged life table for males and females combined is shown in Table 5 below.

A complete life table contains data for every single year of age from the age of 0 at birth until the age of 100 years. A single row of data is included for those who live longer than 100 years. An abridged life table contains data by intervals of 5 or 10 years of age with an initial interval of 0-1 years to account for infant mortality.

The probability of dying is based on the age-specific crude death rate for each age interval. The radix of the abridged life table, or the initial births at age 0, is set by convention at 100,000 births. The probability of dying is applied to the number of people still alive at the start of each age interval which, in turn, provides the number of deaths within that age interval. The remaining number of survivors shift to the next age interval and calculations of subsequent survivors in each age interval proceed down the column.

Table 5: Example of Abridged Life Table

By age	Probability of dying	Number of people left alive at age	Number of people dying	Person-years lived between ages	Person-years lived above age	Expectation of life at age (Years)
0 Years	0.00274	100,000	274	99,772	8,268,809	82.7
1-4 Years	0.00060	99,726	60	398,769	8,169,038	81.9
5-9 Years	0.00044	99,666	44	498,210	7,770,268	78.0
10-14 Years	0.00041	99,622	41	498,017	7,272,059	73.0
15-19 Years	0.00101	99,581	100	497,685	6,774,042	68.0
20-24 Years	0.00152	99,481	152	497,046	6,276,357	63.1
25-29 Years	0.00210	99,329	209	496,144	5,779,311	58.2
30-34 Years	0.00273	99,120	270	494,954	5,283,167	53.3
35-39 Years	0.00379	98,850	375	493,367	4,788,213	48.4
40-44 Years	0.00563	98,475	554	491,082	4,294,846	43.6
45-49 Years	0.00887	97,921	869	487,594	3,803,765	38.8
50-54 Years	0.01337	97,052	1,297	482,176	3,316,171	34.2
55-59 Years	0.01933	95,754	1,851	474,385	2,833,995	29.6
60-64 Years	0.02784	93,903	2,615	463,374	2,359,609	25.1
65-69 Years	0.04330	91,288	3,953	447,244	1,896,235	20.8
70-74 Years	0.07371	87,335	6,437	422,160	1,448,991	16.6
75-79 Years	0.14001	80,898	11,326	378,386	1,026,831	12.7
80-84 Years	0.25410	69,572	17,678	306,270	648,445	9.3
85-89 Years	0.42124	51,894	21,860	205,263	342,175	6.6
90-94 Years	0.61667	30,034	18,521	100,808	136,912	4.6
95-99 Years	0.79336	11,513	9,134	30,864	36,104	3.1
100 Years old & over	1.00000	2,379	2,379	5,240	5,240	2.2

The number of person-years lived between each age interval are calculated taking into account the spread of deaths during each age interval. This data is then used to calculate the number of person-years lived above an age interval which, when divided by the number of people in that age interval, gives the remaining life expectancy for that age interval. In the example abridged life table, the average life expectancy at birth is 82.7 years. People in the 50-54 age interval have a remaining life expectancy of 34.2 years. The older one lives, the greater are the prospects of living to an age older than the average life expectancy at birth.

A population with a high crude death rate has a corresponding low average life expectancy. With improvements in nutrition and medical care, the crude death rate of a population could decline to as low as 5 deaths per 1,000 people per year and the corresponding average life expectancy of the population would increase to 80 years and older. Figure 12 below shows the world crude death rate and average life expectancy from 1960 to 2016.

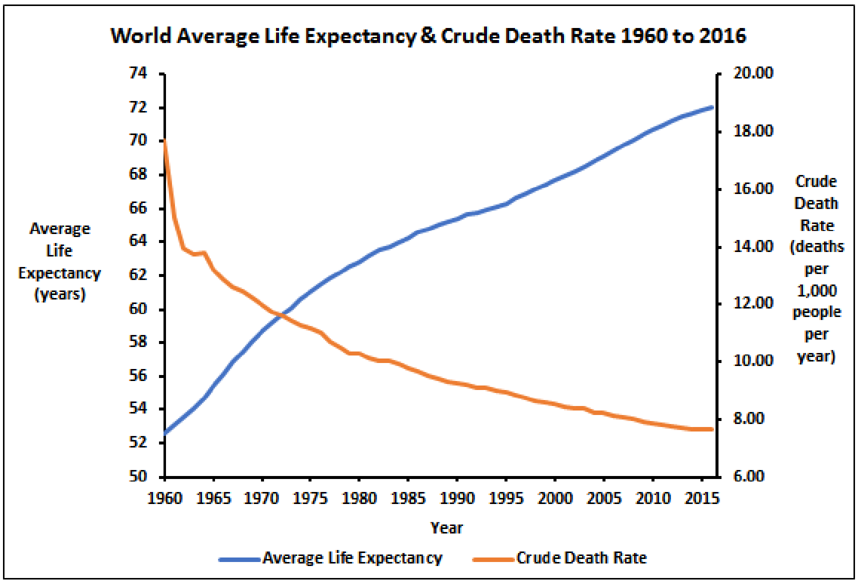


Figure 12: World Average Life Expectancy & Crude Death Rate 1960 to 2016 (Data: United Nations 2019)

The world average life expectancy increased monotonically from 52.6 years in 1960 to 72.0 years in 2016. At the same time the world crude death rate decreased from 17.74 to 7.75 deaths per 1,000 people per year.

Figure 13 below shows the world average life expectancy and rate of change from 1960 to 2016. The most rapid increase in average life expectancy occurred prior to 1967. The rate of increase then continued to decline until 1993 by which time the average life expectancy had improved to 65.9 years. Subsequent improvements to the world total average life expectancy sped up again until 2006 and then slowed down until 2016 when the rate of increase in average life expectancy was 0.25% per year.

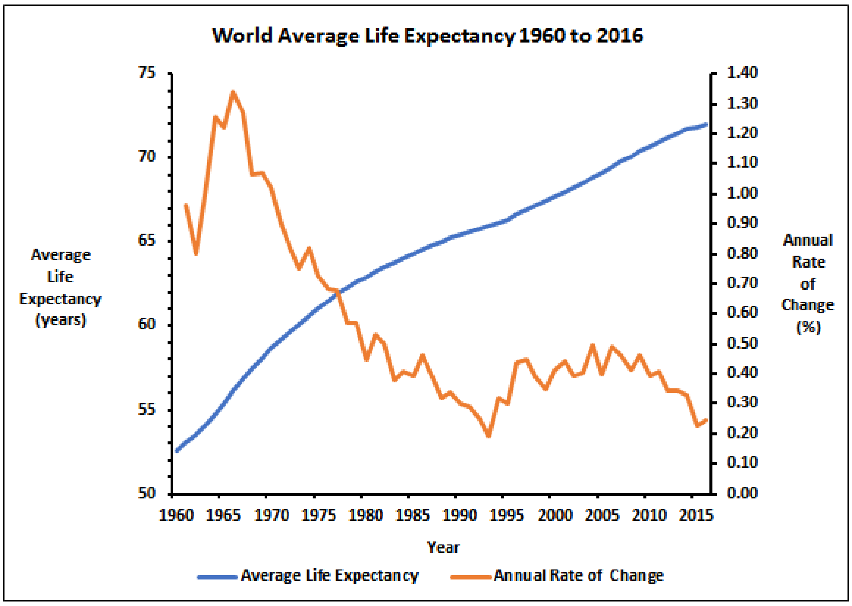


Figure 13: World Average Life Expectancy 1960 to 2016 (Data: United Nations 2019)

Females tend to live longer than males and the average life expectancy of the world female population in 1960 was 54.6 years compared to 50.7 years for males. These average life expectancies improved to 74.3 and 69.6 years respectively by 2016.

The crude death rates in low-income countries tends to be higher than that in high-income countries and this is reflected in the lower average life expectancy. Figure 14 below shows the average life expectancy for combined males and females in high-income, middle-income, and low-income countries.

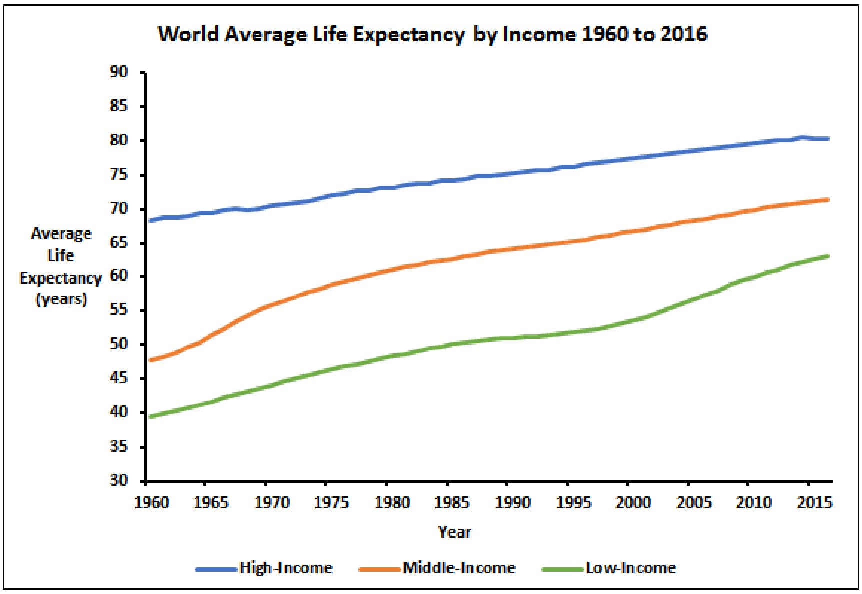


Figure 14: World Average Life Expectancy by United Nations Income Classification 1960 to 2016 (Data: United Nations 2019)

In 1960 the average life expectancy in high-income, middle-income, and low-income countries was 68.4 years, 47.7 years, and 29.5 years respectively. The gap between the average life expectancy in high income countries and that in middle-income and low-income countries was 20.7 years and 28.9 years respectively.

By 2016 the average life expectancy in high-income, middle-income, and low-income countries was 80.4 years, 71.3 years, and 62.9 years respectively. The gap between the average life expectancy in high income countries and that in middle-income and low-income countries had closed to 9.1 years and 17.5 years respectively. Improvements in average life expectancy was due to a decrease in infant mortality, especially in low-income countries, and a general decline in mortality with age.

AGE DEPENDENCY RATIO

The age dependency ratio is the ratio of the number of dependents in a population younger than 15 or older than 64 to that of the working-age population aged between 15 to 64. The age dependency ratio is given as the proportion of dependents per 100 working-age people in the population. If the age dependency ratio is 50%, then there are two working-age people in the population for each dependent. Figure 15 below shows the world age dependency ratio and rate of change from 1960 to 2017.

The world age dependency ratio of 73.5% in 1960 peaked to a level of 77.0% in 1967 in parallel with rapid growth in the world population and then declined monotonically to 54.0% in 2014 with a gradual increase to 54.4% by 2017. The rate of change has fluctuated with a dominant slowdown from 1980 to 1996, a speedup from 1996 to 2005, and then a second slowdown until 2014 after which the world age dependency ratio started to increase.

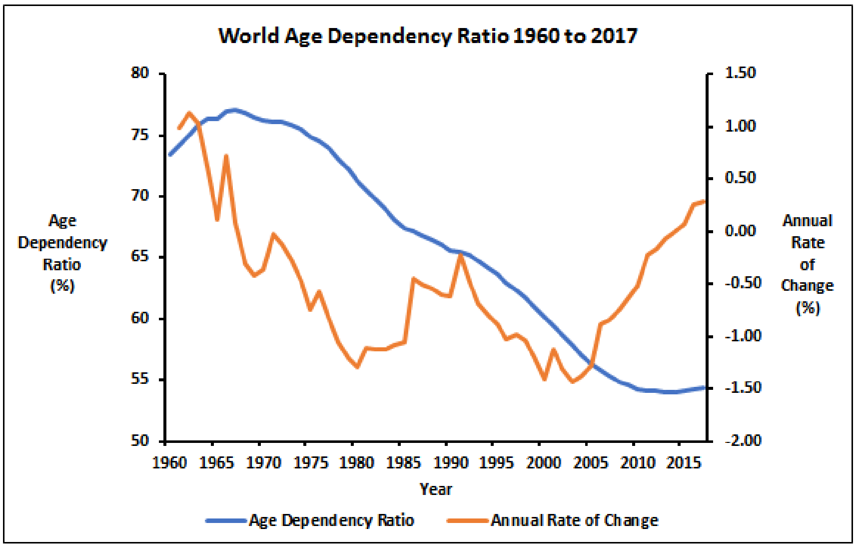


Figure 15: World Age Dependency Ratio and Rate of Change 1960 to 2017 (Data: United Nations 2019)

A decline in the age dependency ratio has the potential to alleviate the burden of the working-age population to support those who are dependents. Figure 7 on page 8 showed the age composition of a rapid growth and a ZPG population which, for the sake of comparison, were set to be subject to the same mortality as that of the New Zealand population in 2016. Table 6 below shows the age dependency ratios for these two example populations and the world population in 2014.

Table 6: Age Dependency Ratios of a Continuous Rapid Growth, a ZPG, and the World 2014 Populations

	Continuous Rapid Growth	ZPG	World 2014
Age Dependency Ratio (%)	66.1	72.5	54.0
Ratio of Children under 15 to Working-Age (%)	56.0	30.6	41.0
Ratio of Adults over 65 to Working-Age (%)	10.1	41.8	13.0
Ratio of Children under 15 to Adults over 65	554:100	73:100	315:100
Average Life Expectancy (years)	81.5	81.5	72.0

The world population has undergone a major transition during the 20th century. After many centuries of slow growth and then many decades of rapid growth as shown in Figure 1 on page 1, the growth rate has declined more or less monotonically since 1971 as shown in Figure 5. The transition from a rapid growth world population prior to 1971 to a world population with a declining growth rate has resulted in a substantial decrease in the world age dependency ratio from 77.0% in 1967 to 54.0% in 2014.

The ratio of children in the world under the age of 15 in 2014 to those of working age is less than that in the continuous rapid growth population example due to a lower growth rate since 1971. The ratio of adults in the world over the age of 65 to those of working age is greater than that in continuous rapid growth population example because these cohorts are the survivors of cohorts born during a period of rapid growth before 1971 rising up through the age composition stack of cohorts. This proportion is greater even though the average life expectancy of the world population in 2014 (72.0 years) was less than that of the continuous rapid growth population example set to be 81.5 years.

The gradual increase in the world age dependency ratio from 54.0% in 2014 to 54.4% in 2017 is a signal of a further transition. The world population has yet to fully transition to a ZPG population. If the world population continues to fully transition to a ZPG population and human mortality in all countries improves to the same level as that of the New Zealand population in 2016, then the ratio of adults over the age of 65 in all countries to those of working age would eventually undergo an almost three-fold increase. The ratio of children under the age of 15 to those of working age would simultaneously undergo an almost 25% reduction. In 2014 there were almost 315 children in the world under the age of 15 for every 100 adults over the age of 65. In the above ZPG population there would be almost 73 children in the world for every 100 adults over the age of 65. The resulting age dependency ratio would increase from 54% in 2014 to about 73%.

A higher age dependency ratio might suggest an increase in the burden of the working-age population to care for dependents. However, this is not necessarily the case. A lower age dependency ratio merely indicates the potential for a larger proportion of the total population to be working for income to support dependents compared to a higher age dependency ratio. There are many factors which determine what proportion of working-age people actually do work for an income and whether the level of their income results in an increase or decrease in the burden to care for dependents. Caring for dependents also involves time and sacrifice by those who do not generate an income. Whether a reversal in the age dependency ratio to previous levels of the early 1960s would actually increase the burden of care for dependents requires close examination.

NET MIGRATION

Net migration is the net total of migrants over time - the total number of immigrants less the total number of which include both citizens and noncitizens. Net migration statistics in Figure 16 below apply over five-year intervals.

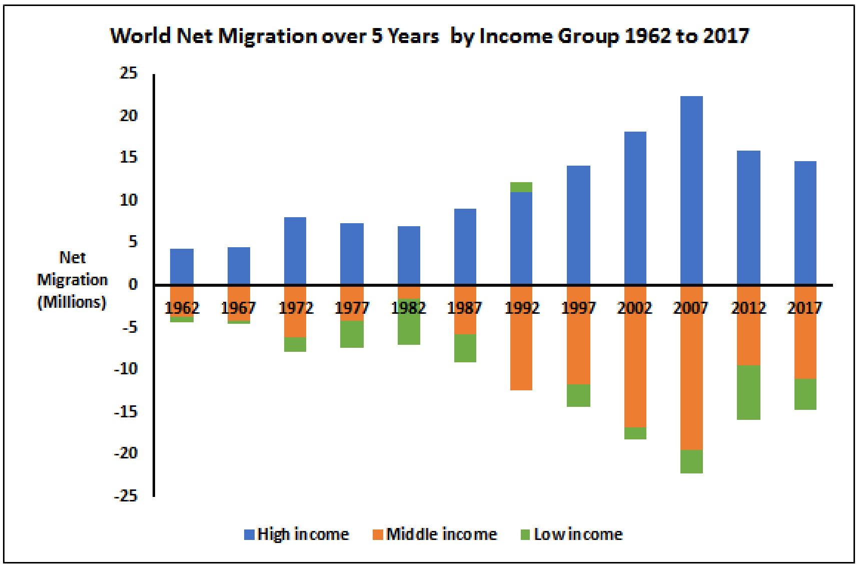


Figure 16: World Net Migration 1962-2017 (Data: United Nations 2019)

Figure 16 shows that apart from the five-year period ending in 1992 when net migration was positive in low-income countries, millions of peoples from middle-income and low-income countries emigrated to high-income countries with a peak in the five-year period ending in 2007. The reasons for emigration are various including the wish for greater work opportunities and lifestyle of high-income countries, the need to flee from war-stricken zones to countries of safety, and the consequences of climate change which has resulted in climate change refugees.

URBANISATION

Urban population refers to the percentage of people living in urban areas as defined by national statistical offices. The data are collected and smoothed by the United Nations Population Division.

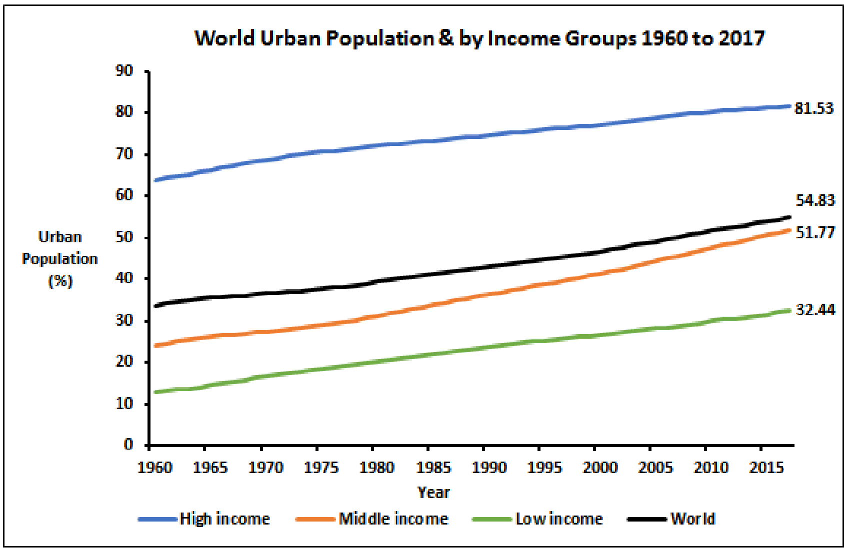


Figure 17: World Urban Population & by Income Groups 1960 to 2017 (Data: United Nations 2019)

Prior to 1960 the group of high-income countries were already highly urbanised (63.8%) and urbanisation continued to increase to 81.5% by 2017. The populations in the group of low-income countries were primarily rural (12.8% urbanised) and over the next 57 years urbanisation increased to 32.4%. The majority of the world's population in the middle-income countries were also primarily rural in 1960 (24.0% urbanised) and transitioned to a significantly higher level of urbanisation (51.8%) than low-income countries.

Population density is the mid-year population divided by land area in square kilometres.

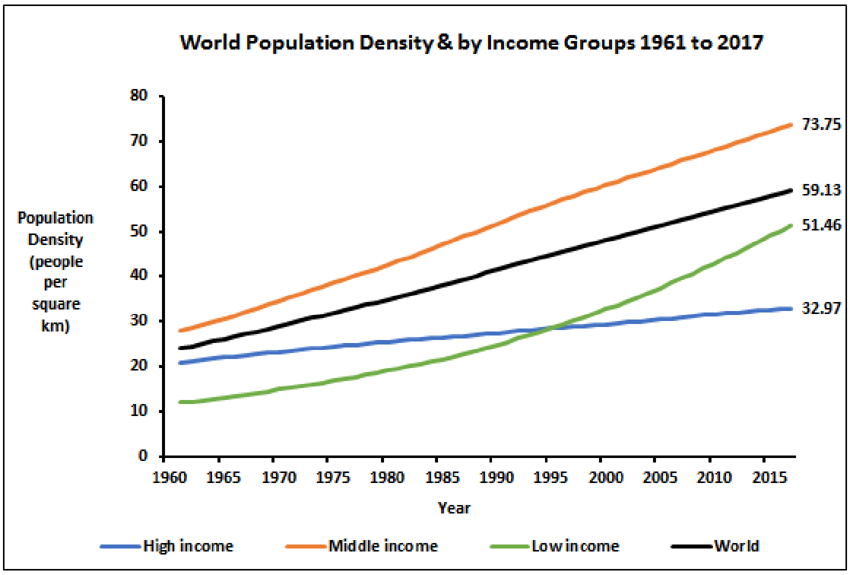


Figure 18: World Population Density & by Income Groups 1961 to 2017 (Data: United Nations 2019)

The low-income countries had the lowest population density in 1960 compared to the middle-income countries (12.0 vs 28.0 people per sq.km.) and these population densities increased to 51.5 and 73.8 people per sq. km. respectively. The degree of both increases in population density follow that of increases in population growth. The population density of high-income countries was mid-way between that of low-income and middle-income countries (21.0 people per sq. km.) and finished up at 33.0 people per sq. km.

due to a much lower increase in population over 57 years. A more significant statistic is the ratio of people to cultivatable land as this is a better indicator of a country's ability to be self-sufficient in food production.

PROSPECTS & PATHWAY TO ACHIEVING WORLD ZPG

All self-regulating systems use negative feedback processes to counteract the positive feedback processes which would otherwise drive the system towards self-destruction. This includes nature where ecosystems are prevented from exceeding their carrying capacities with the negative feedback process of succession, the gradual and orderly process of change in an ecosystem brought about by the progressive replacement of one community by another until a stable climax is established.

In the distant past, continued growth of human populations was limited and restricted by human intervention by way of the practice of abortions, infanticide, war, and the casting out of the elderly from the community. Nature also intervened by way of disease, pestilence, and famine. If humankind is to continue to survive for many more millennia, and if humans are to live a peaceful and joyful life and die a natural death, then humankind has no choice but to monitor and regulate its reproduction cycle so that the number of births each year do not exceed the number of deaths.

Self-regulation of our reproduction cycle can be voluntary or by way of coercion. Methods of birth control include abstinence and contraception. Putting morality aside, if contraception fails, then abortion is a backup. The ultimate contraception is sterilisation which is a less invasive procedure for a male partner than a female partner. Sterilisation of only a male partner does not prevent further births by a female partner.

I advocate responsible family planning and I prefer voluntary self-regulation. With regards to curbing and monitoring population growth, the catch-phrase of think globally, act locally translates into a local community being a group of responsible parents who restrict their average family sizes to replacement level of about 2.11 children per family. In order to maintain a ZPG population, there is no reason why some families cannot and should not have more than two children. After all, some couples will choose to have no children and some females and males will be infertile. The mechanics of ensuring that the average family size does not rise above replacement level is the issue and not the number of children born into any particular family.

The decline in total fertility in the high-income countries below replacement level has not been due to coercion by government, social pressure, or any conscious majority awareness of the need to curb population growth. There is a strong relationship between the level of income of a country and its total fertility where a high level of national income tends to be accompanied by a low total fertility. The middle-income and low-income countries have a long way to go before they achieve the same high levels of income and low levels of total fertility. Financial support from high-income countries would accelerate the closing of the gap.

Several organisations have estimated projections of the world's population. All projections agree that the world population in the future will be bigger though increasing in size less rapidly, will be more urban, and will be an older population (Bongaarts & Bulatao, 2000). The United Nations *World Population Prospects* 2017 Revision states:

> "… the analysis has concluded that, with a certainty of 95 per cent, the size of the global population will stand between 8.4 and 8.7 billion in 2030, between 9.4 and 10.2 billion in 2050, and between 9.6 and 13.2 billion in 2100. … there is roughly a 27 per cent chance that the world's population could stabilize or even begin to fall sometime before 2100."

Projections are not predictions and are based on many assumptions (Cohen, 2002). Some projections are less likely than others depending on the extent that the population of a country surpasses the carrying capacity of the local environment and its dependence on imported food, water, and other critical resources. Political strife between countries is also highly unpredictable and control of fossil fuel supply chains and the peaking of fossil fuels and minerals will become major issues. Whatever the future holds in store for us, continued growth in the world population before 2100 is inevitable unless dire consequences of climate change, inadequate access to energy be it fossil fuels or renewable energy, political strife, and over-reaching the carrying capacity of a local environment take over. All that current and future generations can do during a transition to ZPG is to be better prepared and become more resilient to change.

REFERENCES

Bongaarts, J. and R.A. Bulatao, Editors. *Beyond Six Billion: Forecasting the World's Population*. Washington D.C., National Academy Press, 2000.

Cohen, J.E. *How Many People can the Earth Support?* New York, Norton & Company, 1995.

Cohen, J.E. *World Population in 2050: Assessing the Projections*. Federal Reserve Bank of Boston, v. 46, 2002.

Hyde (History Database of the Global Environment) sourced from Our World in Data website: https://ourworldindata.org/world-population-growth/

Keyfitz, N. 'On the Momentum of Population Growth', *Demography,* v.8, No. 1, 1971, pp. 71-80.

Keyfitz, N. and H. Caswell. *Applied Mathematical Demography*. New York, Springer, 3rd edition 2005.

Meadows, D.H., D.L. Meadows, J. Randers, and W.W. Behrens. *The Limits to Growth*. London, Earth Island Ltd., 1972

Our World in Data website: https://ourworldindata.org/world-population-growth/

Statistics New Zealand website: https://www.stats.govt.nz

United Nations 2019 website: https://population.un.org/wpp/Download/Standard/Population/

United Nations. *World Population Prospects: The 2017 Revision, Key Findings and Advance Tables. ESA/P/WP/248*. United Nations Department of Economic and Social Affairs, Population Division, 2017.