Two hundred barrels left:
an analysis of population growth, oil reserves and carbon dioxide emissions

Martin J. Blunt
Department of Earth Science and Engineering
Imperial College London
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1. Preamble

When I first wrote these notes in March last year, the oil price is over $100 a barrel[1], which even in real terms exceeds the peaks experienced during the oil crises of the 1970s and early 1980s. This high price is combined with a growing realization that the world cannot easily increase oil production: no longer is it realistic to presume that OPEC can simply 'turn on the taps' and allow more oil to gush onto the markets to calm the price spikes. We are not faced with high oil prices because of a politically-inspired embargo or war (although the debacle in Iraq does not help), but because there genuine shortage while demand continues to increase as the growing economies of China, India and elsewhere aspire to the wealth and life-style enjoyed in the US. Since then, of course, the oil price has collapsed – with the worldwide economy – and has now recovered to around $70 per barrel. In the long run, the reduction in oil price, which suppresses long-term investment, has made the problem of lack of supply once the economy recovers even worse. Allied to this is concern that, in any event, we need to decrease our consumption of fossil fuels to avoid dangerous climate change. In addition, with a population of 6.7 billion, growing by around 80 million every year (this is more than the population of the UK), there is worry over how we can even feed all the people on the planet, let alone offer them the two-car, jet-around-the-world lifestyle we take for granted. This is reflected in record food prices: the wheat price has more than doubled from less than $0.2 per kg[2] in March 2007 to more than $0.4 per kg a year later, causing concern over the ability to feed the world's poor.[3] The new Government Chief Scientist, John Beddington, in his first major public speech, described food security as the most pressing problem facing the world.[4] As people become more prosperous, there is a tendency to covert from a largely vegetarian diet to one richer in meat and diary products. These domestic animals are generally fed on grain that otherwise could be used directly for food – instead as little as 10% of the calorific content of the feedstock is converted to meat and so the overall production of primary foodstuff may need to increase enormously. This is combined with the push to provide biofuels to off-set the shortage of oil, rising population, of course, and fears that production in many regions of the world will decline because of climate change. With this is mind, how will we be able to feed and fuel the world in the future?

These notes will consider the question:

How can we ensure a good quality of life for the world's population this century?

Or at least, it will examine the threats that might prevent this.

To put the question another way, let's consider the medium to long-term future: say the period 2050-2100 compared to the year 2000. Qualitatively there are three scenarios:

1. The majority of the world's population enjoy a standard of living that is as good, or better, than that enjoyed presently in the developed world. Overall the average quality of life for the world's population will continue to improve.

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[1] http://www.guardian.co.uk/business/2008/mar/07/commodities.oil: "US light crude for April delivery rose $1.02 to an all-time high of $106.49 a barrel" on Friday 7 March 2008. It is interesting to note in the article that the Saudi Oil Minister describes the high price as due to 'speculation'; OPEC will not increase its production. The article fails to analyze why this is the case: it is not a question of OPEC being obstinate in the face of growing demands for more oil – the Saudis, and others, simply are not able to boost production.

[2] http://en.wikipedia.org/wiki/Bushel. Units will be a problem throughout these notes, and trying to decipher raw data into anything that is remotely sensible is always a challenge. Wheat prices, in the US, are quoted in $ per bushel. A bushel is a unit of volume, representing approximately 35 l, or 0.035 m^3. However, it is applied as a unit of mass, using a standard density for different commodities. For wheat a bushel is really 60 lb or around 27 kg.

[3] http://news.bbc.co.uk/1/hi/business/7264653.stm#subject: "Wheat prices have hit record highs and tight supplies of the staple crop have ignited concern about rising food costs."

[4] http://www.guardian.co.uk/science/2008/mar/07/scienceofclimatechange.food: "Food crisis will take hold before climate change." John Beddington was previously Professor of applied population biology at Imperial. He was head of the ill-fated T H Huxley School of the Environment, Earth Sciences and Engineering, 1998-2001, and it was he who appointed me to Imperial College.

2. Many people in the world enjoy a high standard of living, but there is still significant poverty and overall the average quality of life for the world's population is not significantly better, or worse, than in 2000.
3. The quality of life for most of the world's population is significantly worse than in 2000.

These scenarios deliberately use vague terms, such as 'quality of life.' It is possible to replace these by quantitative indicators, such a life expectancy, infant mortality, GDP per head, access to clean water, per capita calorie consumption, proportion of the population living in absolute poverty and so on. Since these are broad-brush statements, the expectation is that compared to the year 2000, these indicators will have improved in scenario 1, be much the same (some may improve while others decline) in scenario 2 and be worse in scenario 3.

Before we start though, we do need to agree on the following observations as a baseline for the analysis:

1. All three of the scenarios listed above are possible. If we are sure that living standards will continue to increase there is nothing to worry about and the analysis that follows is redundant and unnecessarily pessimistic, or simply unrealistic bearing in mind the uncertain course of human history and technology. There is some justice to this comment: imagine that you were trying to predict the next 100 years in 1880. Could you possibly anticipate two world wars, motor cars, aeroplanes and the huge increase in wealth, population and life expectancy? No, instead we would have worried about how to find sufficient pasture to feed all the horses…. Even in 1980, who would have predicted the collapse of the Soviet Union and the internet? My answer to this is that we are living through an age analogous to classical Greece associated with a flowering of intellectual discovery. The attendant rapid development of technology is unprecedented in history. However, this cannot continue unabated and we will either out-run our resources and collapse, or reach some prosperous stability using – essentially – technology similar to today's, but applied more sustainably. Which leads to the next point:
2. While technology will develop, we cannot rely on some radically new invention to solve our problems. Examples here include fusion power to provide us with unlimited, cheap energy, crops that convert virtually 100% of the energy from incident sunlight into usable biomass. This might happen and it is certainly worthwhile to try to make these technologies work, but it is unsafe to assume that they will rescue us.
3. Any sensible discussion must discuss population. Many analyses of resources either ignore population growth or dismiss it as irrelevant, while in others it takes centre stage. It is silly to pretend that the earth can sustain an effectively limitless number of people in arbitrary luxury, so we do need at least to consider population and population growth, even if we conclude that it is not the most pressing problem.
4. The quality of life for most people on the planet – by whatever measure (life expectancy, wealth, freedom from disease, diet) – has improved enormously, particularly in the last 60 years. While a significant proportion of the world live in poverty that those of us in rich countries would find totally unacceptable, overall prosperity has increased enormously. This is an important baseline for what follows: while things might get worse, they start from a situation where things are improving.
5. Related to point 1, scenarios 2 and 3 are not inevitable. In particular, if you conclude that life will substantially deteriorate and there is nothing, collectively, that society can or will do to prevent this, then any discussion of the future takes on a rather different perspective. My assumption is that decisions on how to make scenario 1 more likely will focus on collective actions that will help everyone. If scenario 3 is inevitable, then decisions are individualistic: that is, rather than, say, advocate increased use of renewable energy, we should all buy guns, a plough and move to a remote farm in Montana. The emphasis on guns in

many of these discussions indicates a desire not so much to ensure a secure future for oneself and ones family – which is perfectly laudable – but to ensure that nobody else can share in it.

To frame the discussion that follows, I will present my third – and final – list of comments. Predictions of the future that highlight possible serious problems and their consequences tend to fall into one of four categories.

1. Too many people. Here the emphasis is on population growth as the source of our problems.
2. We are running out. Here the concern is dwindling supplies of necessary natural resources – these are principally water, food and energy (with an emphasis on fossil fuels and oil).
3. We are ruining the environment. The main focus here is the greenhouse effect and climate change. However, there are other – often related – considerations, such as topsoil destruction, cutting down the rainforest, pollution of drinking water and so on.
4. We are all going to die. This tends to be a more dramatic worry, warning of some essentially unpredictable catastrophe that will wipe out a large fraction of the population: nuclear war, killer disease and meteorite impact are the three favourites.

These notes will address concerns under points 1-3 without claiming that one single factor is more important than the other. Indeed, they are obviously related. This may be a simplistic point, but it is obvious: all things being equal, problems with scarce resources and environmental degradation are worse in proportion to population. Climate change may be less of a problem if we had abundant food and water supply, but if we are already producing as much as we can, then any changes in productivity may be critical.

Point 4 may also be relevant, but for simplicity, I will not assume that some sudden epidemic, an errant asteroid or a sudden and destructive global conflict will affect our analysis. Having said that, scarce resources may indeed lead to increased conflict and war, while poverty and malnutrition make a population more vulnerable to disease.

The focus in these notes will be on the use of simple mathematical models to study population, fossil fuel production and atmospheric CO2 concentrations. I will not claim to study the whole sweep of interrelated topics that have a material bearing on our possible future.

Style

These notes are written in a pedagogical style. That is, the purpose of the notes is to allow you to analyze different data sources to study population, fossil fuel production and carbon emissions. The intention is for you to follow the analysis, re-do it and make your own conclusions, not for me to force my own interpretation on you, hidden behind a muddle of impenetrable mathematics, unobtainable data and obscure analysis. The discussion is deliberately quantitative, involving the manipulation of data. In this respect, these notes are different from the wide range of excellent popular books and textbooks related to this discussion that tend to be primarily qualitative and assume no mathematical ability in the reader. Here, yes, there will be equations. And yes, I will use calculus. If you ask me, if you do not understand calculus, then you cannot understand the world.

Data

The analysis in these notes will rely on data for population, fossil fuel production and CO2 emissions. I will only use data that is either in the public domain – ideally available in electronic format from a website – or published in readily available papers and books. Some oil and gas related data is compiled in databases that can only be accessed for a large fee: I will deliberately avoid these sources for two reasons. First, it is not clear that this information is any more accurate than what is already in the public domain. Second, their use makes the analysis essentially irreproducible for anyone else without access to this data – this is one of the problems associated with the analysis of oil production: many of the leading players in this area use proprietary data making it essentially impossible to verify their analysis.

As mentioned above, the purpose of the notes is to allow the reader to follow my arguments and, using the data that is readily available, repeat the analysis and come to his or her own conclusions. This is in contrast to many other approaches to this problem, where the author hides behind a very complex model and more-or-less secret data to come up with a set of 'unique' results that you simply have to accept. Here, if you disagree with my conclusions, then simply take the raw data and interpret it yourself. In many ways, I consider it more important that you understand what I have done and why I do it, than the conclusions I make – these you should be able to arrive at yourself.

2. Population

Figure 1 shows a plot of the world's population as a function of time. Of course, strictly speaking, this is a plot of estimates of the world's population which – even recently – are imprecise. So, before commenting on the graph itself, I will say where the data comes from. The US Census Bureau (2008a) compiles data on world population on a country-by country basis. They also provide a table of estimated world population each year from 1950 with projections to 2050. The population in a given year, is the population mid-year (on 1st July, I presume). In general, data from US Government organizations is public domain, complete and thorough – we will encounter this again when we study fossil fuel production. The USGS (United Stated Geological Survey) is one unfortunate exception, but this can wait until later.

Before 1950, the US Census Bureau (2008b) provides a table with different estimates of world population dating back to the year 10,000 BC. I have plotted the summary UN upper and lower estimates from 1 AD to 1950: these values are similar to those quoted elsewhere.[1]

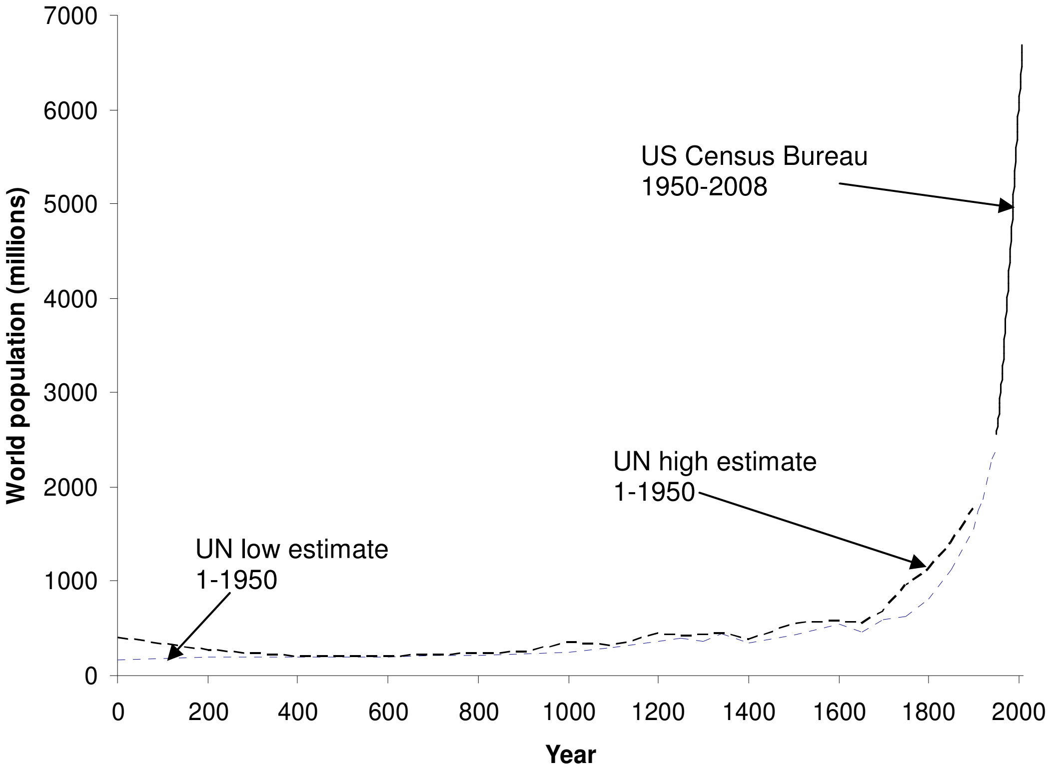

Figure 1. World population from 1 AD to 2008. The data comes from the US Census Bureau (2008a).

The plot of world population seems to show a more-or-less constant population that slowly increases from around 800 AD, starts to rise faster around 1600 AD and has soared recently on a seemingly vertical trajectory: at present (2008) the world population is around 6.7 billion and increasing by approximately 80 million every year. Note too how this one overview minimizes some of the key events in human history: the collapse of the Roman Empire goes unnoticed, as do two World Wars and the discovery of America by Europeans and the consequent death of most of the native population. If you look closely, there is a dip in population after 1340 as the Black Death (plague) swept through Europe; the population did not recover until the 16th Century.

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[1] The source data for the low estimate is similar to Kremer [4] that itself uses McEvedy and Jones [5]. The upper estimate comes from Blaxter [6] that is based on Biraben [7]. Some numbers are adjusted to fit with UN low and high estimates, although these numbers are not apparent on the UN website itself [3]. These values – with some differences – are also quoted in Appendix 2 of Cohen (1995). The conclusion here is that the precise numbers are uncertain, certainly before 1950, but that the range of values provided is – at least – plausible.

The broad sweep of human history is reduced to a sudden, accelerating tide of people over the couple of centuries, preceded by a long period of relative stability; the situation is similar to what we will see for atmospheric carbon dioxide concentrations – quiescence followed by dramatic increase – causing, possibly, a corresponding rapid rise in global temperature.

Growth rates

The population plot – at face value – looks alarming and gives the impression that we are heading for catastrophic and unconstrained increase in the numbers of people on the planet. However, the linear plot of population as a function of time is not the most revealing manner to present the data. More instructive is to compute the growth rate, *g*, defined by:

$$g = \frac{1}{P}\frac{dP}{dt} \qquad (1)$$

where *P* is population and *t* is time.

Before plotting the data, let's comment on the meaning of growth rate. If *g* is constant, then we can solve Eq. (1) to give exponential growth:

$$P = P_0 e^{g(t-t_0)} \qquad (2)$$

where P_0 is the population at some initial time t_0.

Often, the time for the population to double is quoted. From Eq. (2) we define a doubling time $t_d = t\text{-}t_0$ when P/P_0=2:

$$t_d = \ln 2/g \qquad (3)$$

where ln is the natural logarithm and ln 2 ≈ 0.693. If the rate of population growth is 1% per year (*g* = 0.01 per year) then the population doubles every 69 years; if the growth rate is 2%, population doubles every 35 years.

To make this concrete, imagine, for the sake of argument, that on average every woman has four children that survive to adulthood and that the average age at childbirth is 25. Then the population doubles every generation – after 25 years there are twice as many women of childbearing age (assuming that, on average, every woman gives birth to two boys and two girls). The doubling time is 25 years and so, from Eq. (3) the growth rate *g* = ln 2/25 ≈ 0.028 or 2.8% per year. In 2007, the growth rate in the United Arab Emirates was 4%, a doubling time of only 17 years; in Saudi Arabia it was 2.1%; in Rwanda 2.8%; Sweden 0.2%; UK 0.3% (doubling time of 230 years) and the US 0.9% (US Census Bureau 2008c). These growth rates take into account changes in life expectancy, migration and age profile and so cannot be crudely equated with the number of children, but they give an indication of the spread of values across the world.

Figure 2 plots the growth rate over time. We do not, however, have a continuous curve of population. Instead we have values of *P* and *t* and discrete time intervals. I assign a label *n* to the values, such that I have a list of t_n and P_n, where, for instance, *n* = 1 refers to a time t_1 = 1 AD and P_1 is the population estimate for 1 AD. *n* = 2 is the next data point in my series – in this case t_2 = 200 AD – and so on. I have estimated *g* as follows:

$$g_n = \frac{P_{n+1}/P_n - 1}{t_{n+1} - t_n} \qquad (4)$$

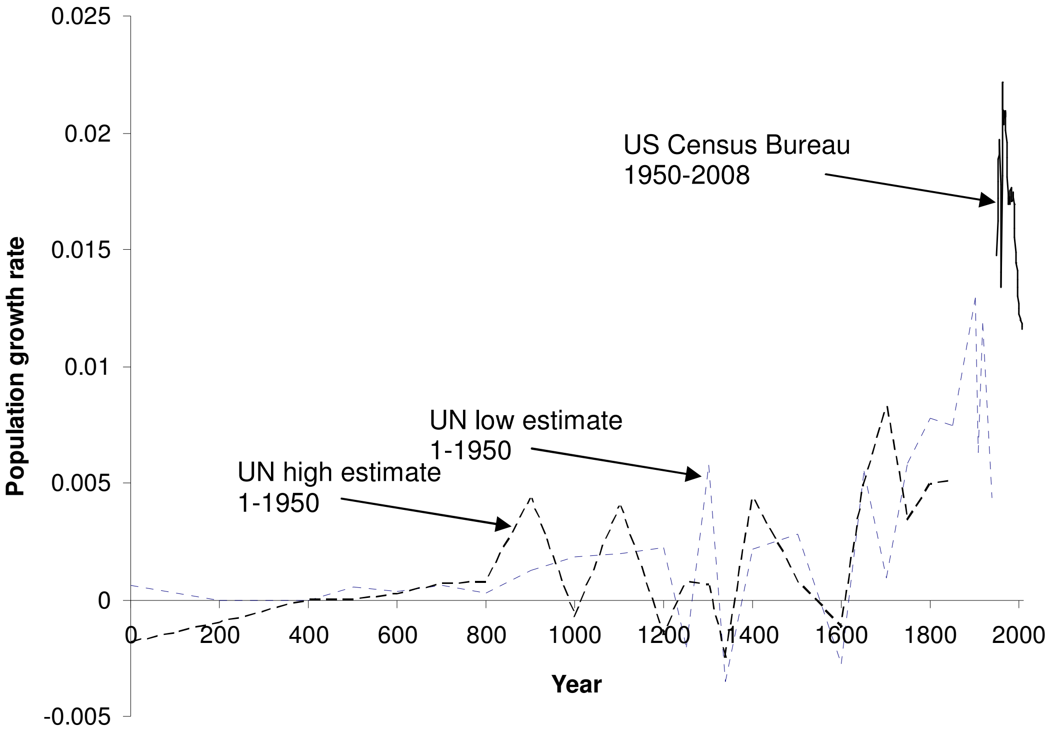

Figure 2. World population growth from 1 AD to 2008. The data comes from the US Census Bureau (2008a) and growth rate is calculated using Eq. (4).

Figure 2 illustrates a growth rate that is fluctuating over time until around 1600, consistent with little growth, followed by a rising growth rate that peaks at over 2% per year before appearing to drop recently. However, the graph compresses recent changes.

Another way to present the data is to plot the growth rate as a function of population itself. This is shown in Figure 3, which tends to give greater emphasis to the more recent data, when the population is larger. There are two generic trends. The first, until 1963, is an approximately linear increase in population growth rate with population, albeit with some scatter due to fluctuations caused by war and famine, as well as considerable uncertainty in the population estimates themselves. Then after 1963 there is a decline in growth rate that is also approximately linear, again albeit with significant variations.

The first observation is that at no time in history has there been a constant growth rate, corresponding to an exponential increase in population – it has either been faster (that is a growth rate that increases with time) or slower (growth rate decreasing with time) with an apparently sudden transition between the two regimes. Hence, the use of growth rates and doubling times can be misleading, since they can imply that these rates are constant and can be used to extrapolate the population into the future: it is evident that such an approach would have under-estimated the astonishingly rapid rise in population in the century to 1960, while over-estimating population subsequently.

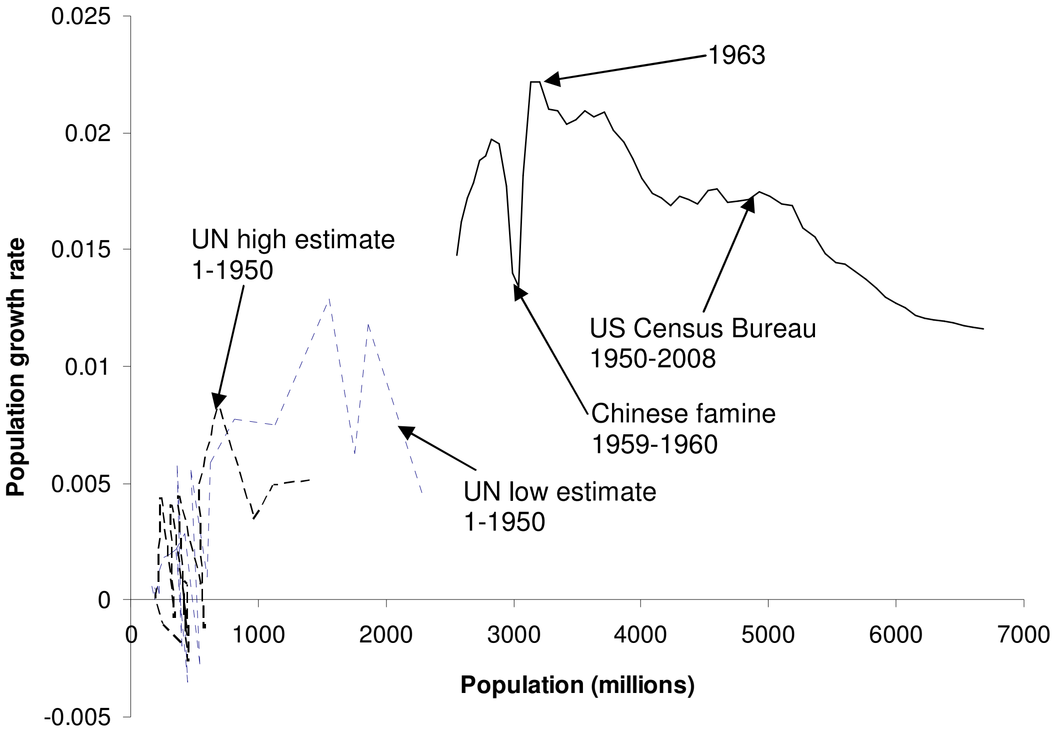

Figure 3. World population growth as a function of population. The data comes from the US Census Bureau (2008a) and growth rate is calculated using Eq. (4). The peak growth rate occurred in 1963, and has been declining since then. The sudden drop in 1959-1960 was due to the Chinese famine.

The interpretation of this behaviour has been discussed previously – see, for instance, the excellent, scholarly work of Cohen (1995). The faster-than-exponential growth until 1963 is largely attributable to technological progress: a larger population was able to support more innovation and provided an infrastructure to make use of advances in agriculture and industry. This in turn generated resources to support a larger and larger population. As the population increased, so did the opportunity for new invention and further advances in productivity. Improvements in diet, sanitary conditions and medicine allowed people to live longer, improved childhood and maternal survival, and reduced deaths from infectious diseases. In most pre-industrial societies with no access to birth control, the average number of children born to a woman was around 6 – this is called the total fertility rate (Livi-Bacci, 2007); without an increase in population only two of these children would survive to have children of their own. Industrialization coupled with improvements in agriculture and health care have resulted in enormous increases in life expectancy, such that almost all children survive to reproductive age. If there is no decline in the number of children – indeed this may increase, as maternal health improves – the population increases rapidly. A stable fertility rate of 6, for instance, and a generation gap of 25 years give a growth rate of 4.4% an a doubling time of just under 16 years.

The world's population did not, however, continue to accelerate; the growth rate has been declining for the last forty years. This phenomenon is called the demographic transition. The world figures give an aggregate across all countries, with different histories of industrialization. In general, a country experiences a period of very rapid growth largely due to a decrease in childhood mortality while the birth rate remains high. Then the birth rate decreases: there are several, often related, reasons for this, including cultural realization that large families are not needed to ensure that some children survive to adulthood; societal constraints on marriage or age of marriage; availability of effective birth control; improvements in education, particularly the education of women; provision of work outside the home for women; and economic reasons for wanting to reduce the number of children. These notes are not principally about population, so my comments will be brief – I wish the analysis to be data driven, and so I will not attempt an in-depth critique of the myriad and complex reasons for different population growth rates in different countries at different times. However, I will provide four specific examples: the US, Sweden, Saudi Arabia and Rwanda. In these examples I will study more recent changes in population for which reliable data is readily available. In all cases I will plot total population and growth rate as a function of time. For Sweden I have taken the data from the Swedish Statistical Office (2008); for all other cases the data comes from the US Census Bureau (2008d).

Population growth in the US

The first example is the US. Figure 4 shows the population from 1790 to the present, while Figure 5 shows the corresponding growth rate. The US population has increased from only 3.9 million to more than 300 million today. While, clearly, it was immigration that led to the settlement of the US by Europeans, throughout the period shown the natural increase in population greatly outweighed the effect of immigration – the population growth is almost entirely due to a high birth rate among the resident population. The only exception is the period 1901-1910 when immigration alone accounted for a growth rate of 1%; at other times, however, immigration contributed 0.2-0.3% to population growth. In the period 1790-1850 the growth rate was above 3%, representing, on average, around 5 children per woman reaching maturity and having children themselves. The reason for this rapid growth is obvious: a vast fertile continent abundant in natural resources was made available to families of European descent. The demographic transition started after 1850, as a more settled, urban population reduced family size. Note, however, that the US population continues to increase at a rate of 1% per year – this is due to continued immigration at a rate of 3 per 1,000 per year, contributing 0.3% to growth rate combined with slightly greater-than-replacement fertility – the total fertility rate in the US is currently 2.1 – an ageing population, and increasing life expectancy.

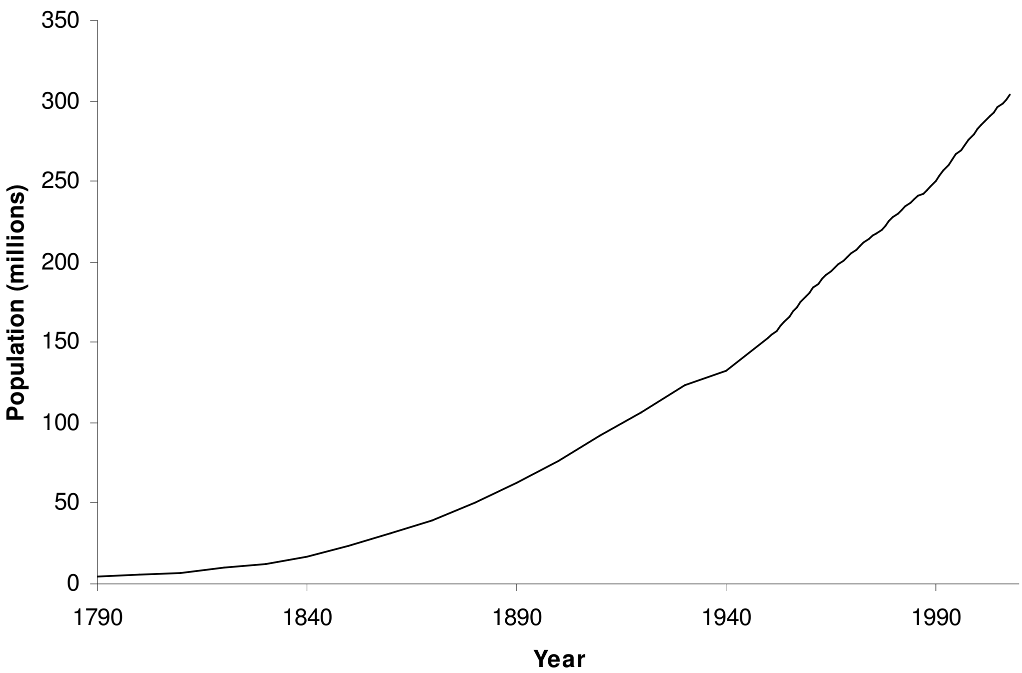

Figure 4. US population from 1790 to the present day. The data comes from the US Census Bureau (2008d). The population of the US is increasing steadily; immigration has had little impact on population growth in this period, except in the first decade of the 20th century.

Figure 5. US population growth rate. Note the very rapid growth in the period from 1790 to 1850. The data comes from the US Census Bureau (2008d) and the growth rate is calculated using Eq. (4).

Population growth in Sweden and other developed countries

My second example is from Sweden – Figures 6 and 7. This represents a country where population growth has remained relatively low throughout the last two centuries. The result is a much more modest increase in population: it was 2.2 million in 1790 – at that time the US population was only 1.8 times larger; the population today has grown to 9.2 million, a significant increase, yet today the US has 33 times more people. The growth rate shows considerable fluctuations, particularly before 1900, with spikes due to war, famine and epidemics when the population decreased. Some of the apparent variability is a statistical artefact though: the Swedish data is available each year, whereas, before 1950, the US data is only shown every ten years and so the corresponding growth rates are averaged over a longer period, providing a smoother graph.

After 1900 the average growth rate decreases slightly and there is less variability with no years where the population decreases – this is a reflection on the decrease in the death rate and less vulnerability to the effects of war, famine and disease. Currently the total fertility rate in Sweden is only 1.7, which is less than replacement. If this is the case, why is the population still increasing, albeit slowly? The reason is due to the age distribution of Sweden (and most other countries). Since life expectancy has increased over time, and the total fertility rate was greater than 2 until recently, the proportion of the elderly in the population is small. Hence the number of deaths among the few old people may be lower the number of births from the relatively larger fraction of women of child-bearing age. In Sweden these two factors almost exactly cancel out – the growth rate is entirely accounted for by immigration; without this, the population would be static. The phenomenon of lower than replacement fertility is common throughout the developed world: in the UK the total fertility rate is also 1.7, but the population is increasing, again largely due to migration; Germany has a fertility rate of only 1.4 and a slowly decreasing population; Italy's fertility rate is only 1.3 and the population is approximately constant; while in Singapore the fertility rate is a mere 1.1, although the population continues to increase, since there are few old people and significant immigration. Russia is the largest country in the world with a significantly declining population – a growth rate of -0.5%, a fertility rate of 1.4, negligible immigration and a life expectancy that is four years *lower* in 2007 than in 1989, before the collapse of the Soviet Union. South Africa also has a growth rate of -0.5%; here the fertility rate is 2.2, but the life expectancy is only 42 thanks largely to the effect of HIV/Aids with a net emigration rate of 0.4% per year.

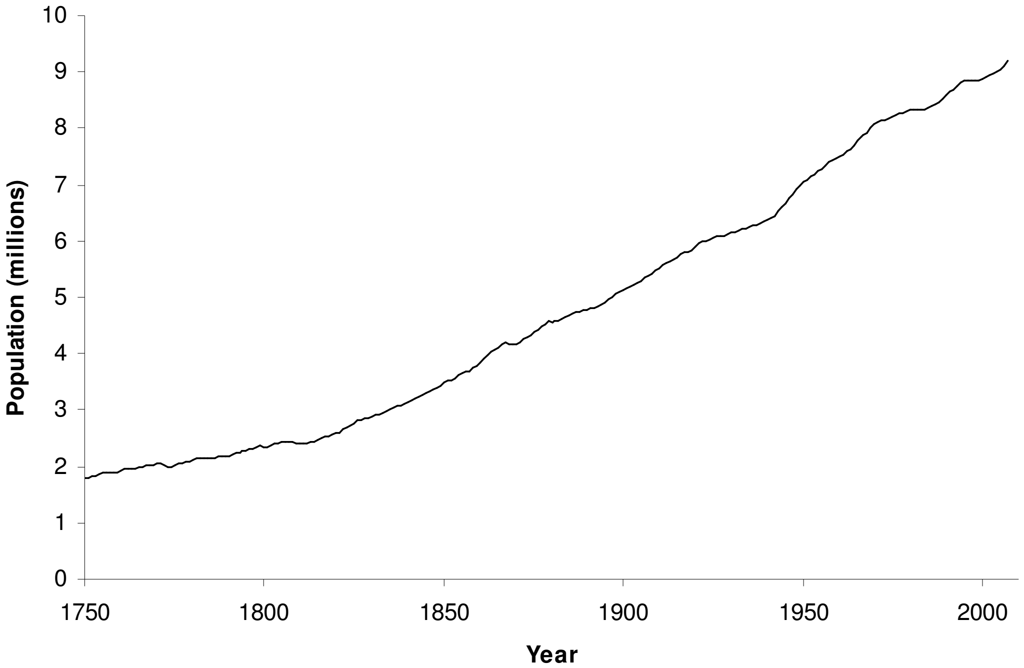

Figure 6. Swedish population from 1750 to the present day. The data comes from the Swedish Statistical Office (2008).

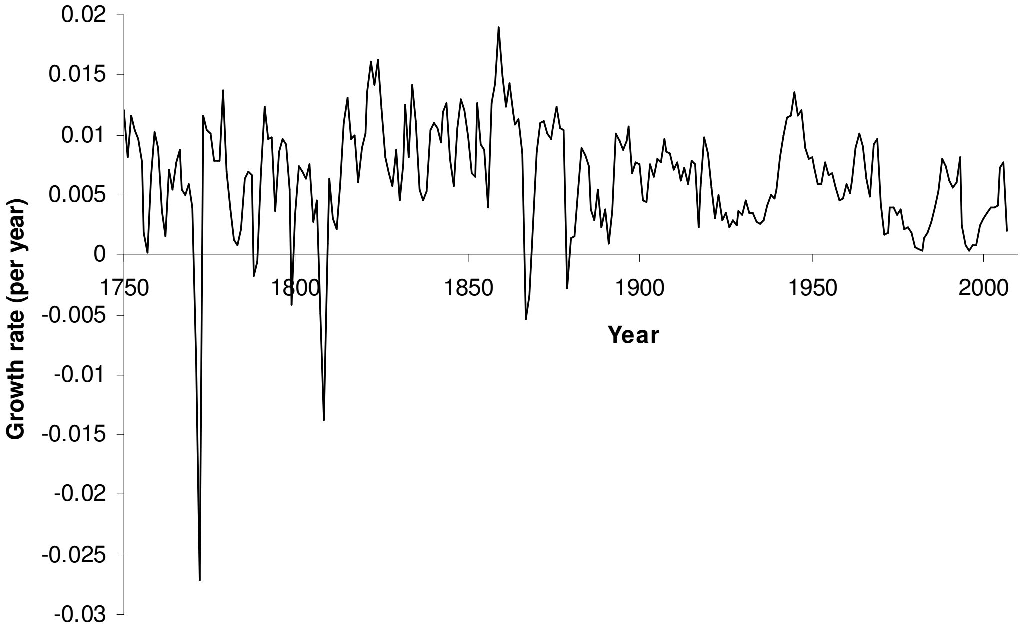

Figure 7. Swedish population growth rate. The data comes from the Swedish Statistical Office (2008) and the growth rate is calculated using Eq. (4). Note that compared to Figure 5, the growth rates trend to be lower than in the US.

Saudi Arabia – yet to experience a demographic transition

Unlike the oil and gas rich Gulf states of Kuwait, Qatar, the United Arab Emirates and Oman that have a small (but rapidly increasing) and prosperous native population, Saudi Arabia is poorer and more populous: it is not just a few rich oil sheikhs living lavishly off oil revenues.

Figures 8 and 9 show the population and growth rate since 1950. The comparison with Sweden, and even the US in its period of rapid growth, is both astonishing and alarming. The growth rate peaked in 1978 at over 7%, giving a doubling time of less than 10 years! However, much of this increase is due to immigration; Saudi Arabia employs a large expatriate labour force. The apparent rapid decline in growth rate around 1990 is principally due to the expulsion of 800,000 Yemeni workers at the time of the Gulf War (McMurray, 1999). The natural growth rate, ignoring migration, has been around 3% per year, decreasing slowly to 2.6% per year in 2008; the total fertility rate has declined from over 7 to around 4 in this period, but is still high by international standards: as an example, the present King Abdullah is one of 37 sons of the founding King of the Saud dynasty, Abdul-Aziz; Abdullah himself has a relatively restrained 22 children (by four wives) (Wikipedia, 2008a). Saudi Arabia is given as an example here as it will be relevant to our subsequent discussion of oil reserves and production.

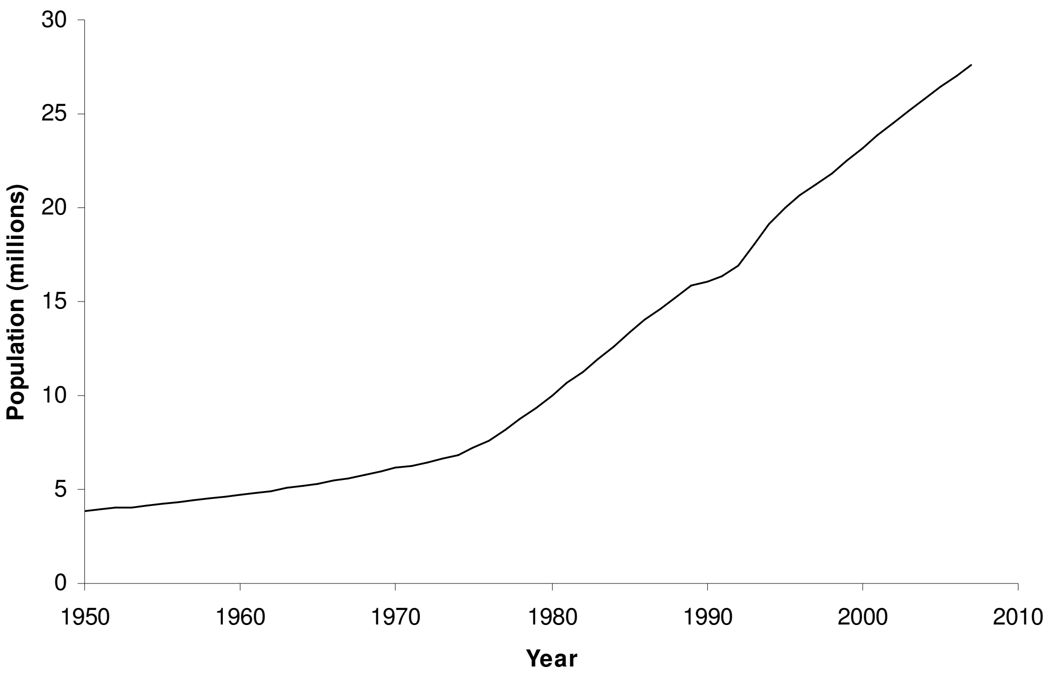

Figure 8. The population of Saudi Arabia from 1950 to the present day. The data comes from the US Census Bureau (2008d).

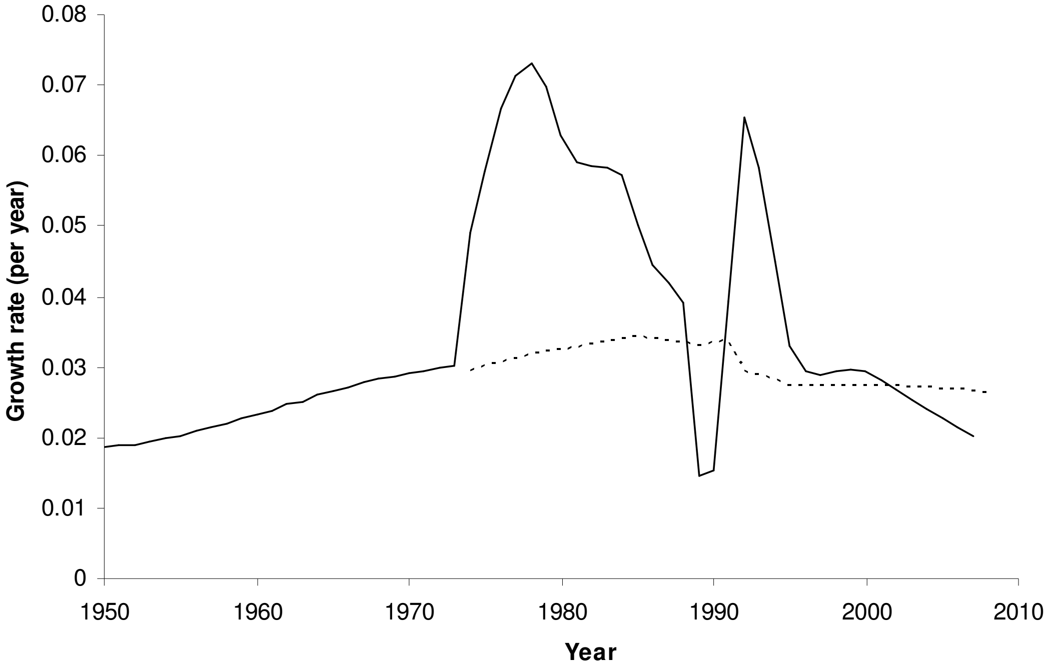

Figure 9. The population growth rate of Saudi Arabia. The data comes from the US Census Bureau (2008d) and the growth rate is calculated using Eq. (4). The dotted line shows the natural growth rate (excluding migration) from 1974: while the growth rate is high, the wide swings have been due to rapid changes in the expatriate workforce of the kingdom.

Rwanda – population growth and tragedy in Africa

Our final example comes from Rwanda as an example with both rapid population growth and decrease. In 1994 after the death of the Rwandan president in a plane crash, there was a systematic killing of minority Tutsis and moderate Hutus by members of the majority Hutu tribe. The genocide ended when a Tutsi-led army invaded the country. Subsequently conflict spread to neighbouring Burundi and the Democratic Republic of the Congo where up to 4 million people have died. In 1994 9.8% of the Rwandan population died while a further 35% fled the country. In the subsequent three years, the net immigration rate was also 35%, coupled with a natural increase approaching 3%. The overall impact on the long-term trend in population is negligible: the killing of an estimated 800,000 – 1 million people represents no more than four years' increase in population. This is concerning, since one of the drivers for the carnage was shortage of available farmland (see, for instance, the excellent description in Jared Diamond's book 'Collapse'): Rwanda has a population density of 380 people per km^2 (or almost exactly 1,000 people per square mile) (US State Department, 2008), the highest in sub-Saharan Africa: for comparison, the population density of the US is 32 people per km^2, the UK is 251, South Africa is 3.6, Bangladesh is 1,066 and the Netherlands 401.

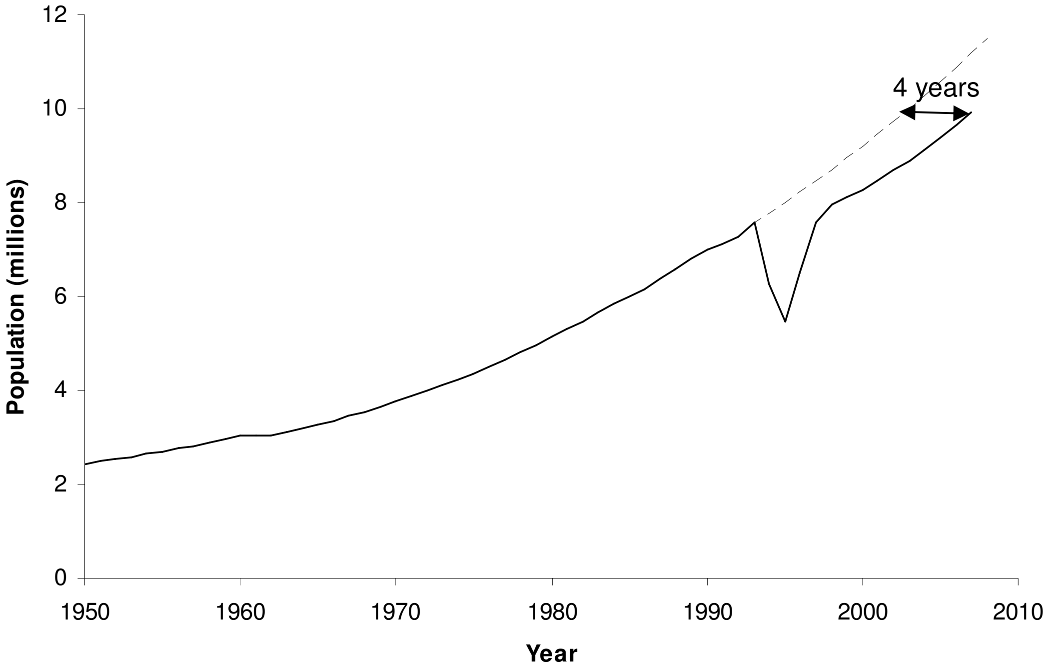

Figure 10. The population of Rwanda from 1950 to the present day. The data comes from the US Census Bureau (2008d). The dashed line shows an extrapolation of the population from 1993 assuming a constant growth rate of 2.8% (the growth rate in 2007). In crude population terms, the genocide has made little difference to the long-term trend, except to delay the population increase by approximately 4 years.

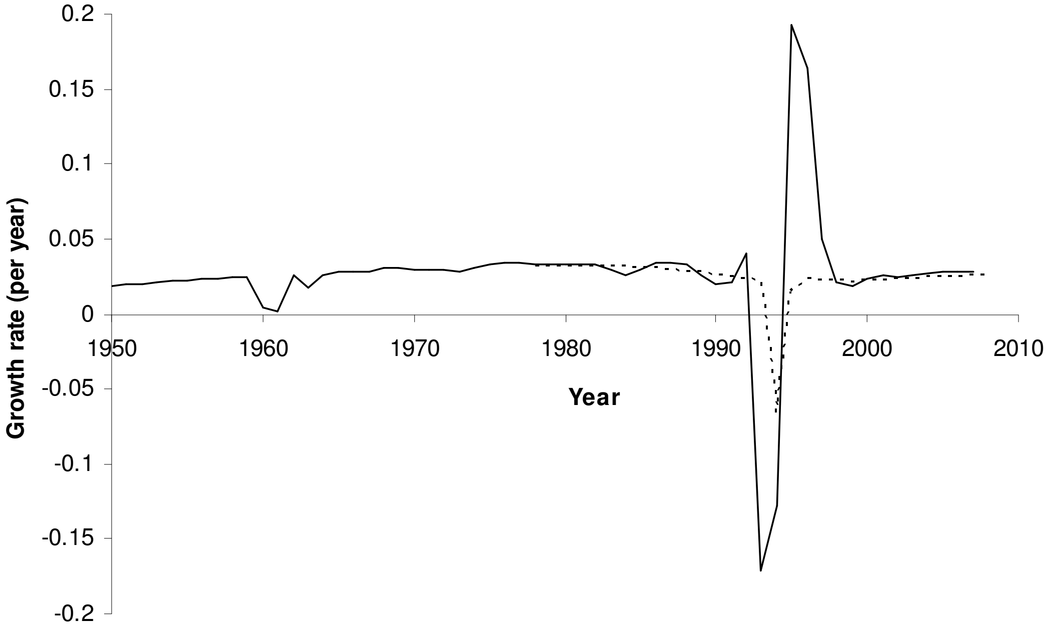

Figure 11. The population growth rate of Rwanda. The data comes from the US Census Bureau (2008d) and the growth rate is calculated using Eq. (4). The large and negative growth rates in 1993 and 1994 are due deaths during the genocide (9.8% of the population in 1994) coupled with net emigration of 35%. The dotted line shows the natural growth rate, excluding migration, from 1978.

Population growth models and extrapolation to absurdity

The previous discussion illustrates that on a country-by-country basis there is considerable variation and the world population graph is the aggregate of many different circumstances. In this section I will attempt to fit the population data using a simple model and use this to predict population in the future. This is little more than a curve fitting exercise with relatively little theoretical foundation, as an analysis at a country level reveals. However, the estimates it produces are instructive to obtain a global assessment of population and serve as a useful introduction to the analysis of oil production which will employ a similar model.

Eq. (1) assumes that there is a constant growth rate. The next simplest model is to assume that the growth rate varies linearly with population, which is not an unreasonable assumption before 1963 (the behaviour after 1963 will be discussed later). Mathematically this is expressed as:

$$g = \frac{1}{P}\frac{dP}{dt} = aP - b; \quad \frac{dP}{dt} = aP^2 - bP \tag{5}$$

with some positive constants *a* and *b*. We can call this the linear model, although a simpler version (with the constant *b*=0) was first proposed by ….. For very small populations (*aP*<<*b*) the population decrease and will, eventually reach zero. We will assume, however, that the model is only valid for *aP*>*b*, in which case the growth rate is always positive and increases with population. Later we will study the opposite case where the growth rate decreases, corresponding to a negative value of *a*.

In Figure 12 the data in Figure 3 is replotted together with a best-fit straight line which I obtain using $a=7\times10^{-12}$ per year and *b*=0.0012 per year.

It is possible to solve Eq. (5) analytically to obtain a prediction for population:

$$\frac{dP}{P(aP-b)} = dt; \quad \left(\frac{1}{P-b/a} - \frac{1}{P}\right)\frac{dP}{b} = dt; \quad \ln\left(\frac{P-b/a}{P}\right) = bt + c \tag{6}$$

with an integration constant *c*, from which we obtain:

$$P = \frac{P_0}{(1-aP_0/b)e^{b(t-t_0)} + aP_0/b} \tag{7}$$

There are two special cases. The first is when *a*=0; this is exponential growth with *g*=-*b* and *P* given by Eq. (2). The second is *b*=0. In this case:

$$P = \frac{P_0}{1-aP_0(t-t_0)} \tag{8}$$

It should be emphasized that these are simply curve-fitting models useful for some fixed range of time and population. As mentioned before, for small populations, Eq. (5) will predict a population that will shrink to zero if *aP*<*b*; hence it is only applicable for populations larger than *b/a*, or 170 million in this case. More importantly, the models cannot be extrapolated far into the future. Unless *a*=0, Eq. (7) or (8) predict that the population will become infinite at some finite time, which is clearly nonsense. This doomsday occurs when:

$$t - t_0 = -\frac{1}{b}\ln\left(1 - \frac{b}{aP_0}\right) \tag{9}$$

which reduces to $t-t_0=1/aP_0$ for *b*=0. Our model gives a good fit to estimated population data using P_0=188 million where t_0 = year 1 – see Figure 13. Then we predict an infinite human population in 2007. All we can say is that this didn't happen!

We are not the first to have noted this linear trend to growth rate and to extrapolate it to absurdity. In the 1960s before the worldwide demographic transition was evident, this seemingly accelerating rise in population was alarming and demographers, using a slightly different fit to the data with b=0, predicted doomsday in 2026.

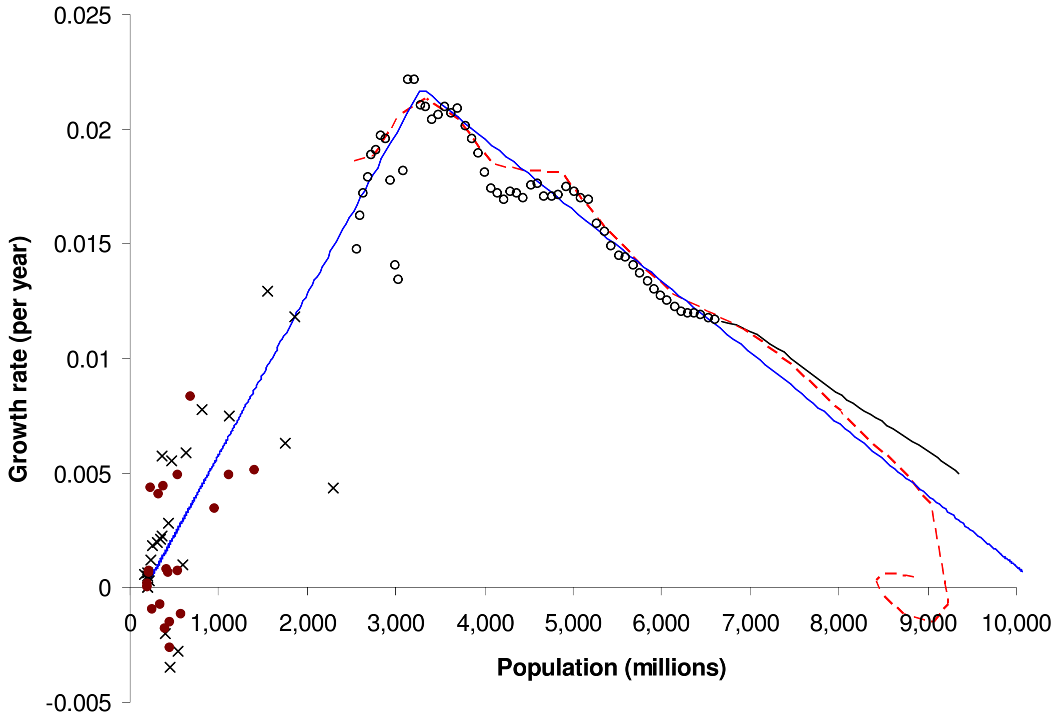

Figure 12. Projected and estimated world population growth as a nction of population. The data comes from the US Census Bureau (2008a) and growth rate is calculated using Eq. (4).

The consequences of exponential growth

Fortunately for humanity, while population has continued to rise, the growth rate is now falling. The population approximately follows a simple and well-known growth model. While our previous model could clearly only be valid for a limited period of time, predicting a declining population below 170 million and a population that became infinite at some fixed date in the future if the population was ever larger than this, even exponential growth leads to absurdities if extrapolated far into the future.

For a concrete example, consider Rwanda. Even if we were to insist the genocide and subsequent regional instability has an entirely political and racial motivation with resource limitation a completely irrelevant factor, the current rate of population growth cannot be sustained, even into the near future. Rwanda growth rate us currently 2.8% per year and has been around this level – apart from the tragedy of 1994 – for the last 50 years. This is a doubling time, Eq. (3), of around 25 years. Hence, if this growth continues, the population of Rwanda will be 20 million in 2033. This might seem possible, since the population density would still be lower than currently in Bangladesh, for instance. However, it is worth bearing in mind that Rwanda is also home to a diverse natural habitats with the mountain gorillas as the most famous resident; not all the land is co-opted for human use. In 2058 the population will be 40 million and the population density will exceed that of any country at present, with the exception of a few small city states. In 2108 the population will be 160 million and 2.56 billion in 2208. In 2258 the population will be over 5 billion and over 10 billion in 2283. Clearly this has to stop at some stage – indeed the extrapolated population in 2283 is similar to what we will predict for the whole world at this time. Exponential growth – even with a small growth rate – cannot continue unabated for ever.

On a worldwide basis, while it is difficult to predict growth rates for the near future, we can be quite certain that over the long term the average growth rate must be very close to zero. Let's estimate the average growth rate over the next 10,000 years, for instance. We will assume that the human race does not die out and confine to discussion to inhabitants of planet earth. It is unlikely that the population will be lower than a tenth of our present population, again assuming that we live in some sort of technologically sophisticated society, nor it is likely to be more than ten times larger. This constrains the growth rate to an absolute value (positive or negative) that is less than 0.023% per year. Compare this with Sweden's relatively stable population with a growth rate of 0.2% per year: if this were to continue for 10,000 years however, the Swedish population would be 202 billion, which is clearly nonsensical. In the long run the growth rate has to come out as very nearly zero.

The logistic equation and carrying capacity

The simplest population growth model that accommodates a constraint on the maximum population obeys the logistic equation. A small population with no resource constraints is assumed to grow exponentially – the US population between 1790 and 1850, shown in Figure 5, is an example. It is further assumed that there is a maximum population that can be supported by the available resources. This is called the carrying capacity that we give the symbol *K*. If the population is equal to the carrying capacity, the growth rate is zero; if it is smaller, the population grows, approaching the value *K*; if it is larger, the population decreases. While there are many ways in which these ideas may be expressed by an equation, one of the simplest, the logistic equation, was first proposed by Volterra in 1567:

$$g = \frac{1}{P}\frac{dP}{dt} = r\left(1 - \frac{P}{K}\right) \tag{10}$$

The constant r is the growth rate for small populations; when $K >> P$, $g \approx r$.

Before proceeding, we should note that Eqs. (5) and (10) are mathematically equivalent. Eq. (10) reduces to Eq. (5) if we set $r=-b$ and $K=-b/a$. The reason for presenting this as a new equation with different symbols is the very different physical interpretation of the equations: the linear model gives a growth rate that increases linearly with population, leading, eventually, to an infinite population in a finite time; the logistic equation has a growth rate that decreases linearly to zero as the population approaches the carrying capacity.

We can use Eq. (7) to write down the solution to Eq. (10):

$$P = \frac{KP_0}{(K - P_0)e^{-r(t-t_0)} + P_0} \tag{11}$$

Logistic growth can be identified by plotting the growth rate as a function of population. If the data lie on a straight line, then from Eq. (10) this gives a slope equal to $-r/K$ and if the line is extrapolated to a growth rate of zero, the population value $P=K$.

Figure 12 shows that world population growth since 1963 has followed, approximately, a linear decrease with population consistent with a carrying capacity of around 10.2 billion and a natural growth rate of 3.2% per year. That the data obey such a simple equation, albeit somewhat roughly, is surprising, since the data country by country is highly variable, as our examples illustrate.

Figure 13 shows our prediction of world population from 1950 using the logistic equation fit after 1963. I will discuss later – under oil – how exactly to perform a logistic equation fit in detail. In this case I took a population at a known date in the past and extrapolated forward using Eq. (11) and my estimated values of K and r. Also shown in Figure 13 are projections of the world population provided by the UN and the World Bank. These projections[1] are considerably more sophisticated than provided here. While the precise methodology varies, it is based on an initial estimate of the number of people of each age. Then birth and death rates by age and gender (only the women bear children!) are used to extrapolate the population into the future. The birth and death rates are allowed to change, reflecting trends in fertility and life expectancy. Sometimes different scenarios are proposed using different assumptions for fertility. What is shown here is the UN mid-range estimate. Generally these projections on a global basis are reasonably reliable: the UN prediction in 1970 for population in 2000 was 6 billion; the population reached this value in 1999. Bearing in mind that the 1970 world's population was 3.7 billion and the growth rate had only recently begun to decrease, this is a reasonably accurate forecast. Other, more expert, analysts seem to consider population predictions as much less reliable, but I am going to assume that they can be used with reasonable confidence to look around 30 years into the future. The prediction used here, based on a simple model, is not meant to rival these more sophisticated methods, but is a useful mathematical device to generate a closed-form mathematical expression for population that works well for the recent past and which is consistent with other estimates; our projection will be used in what follows when we discuss oil production and carbon dioxide.

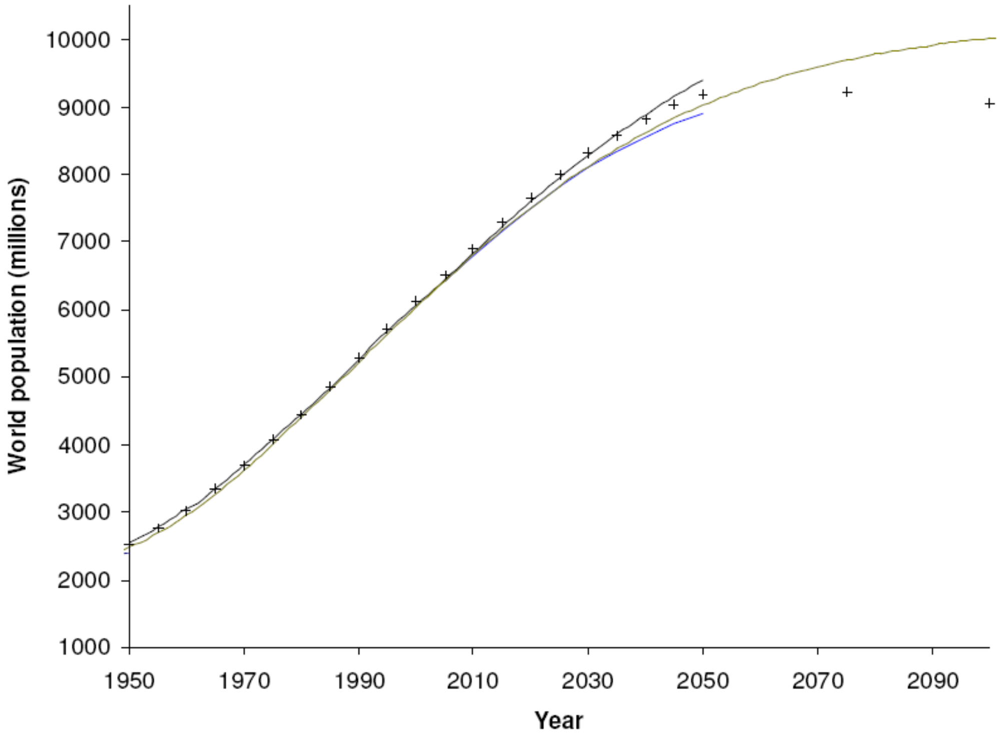

Figure 13. Projected and estimated world population growth. The points are UN data and projections, the upper (black) line is the US Census Bureau data and projections, the lover blue curve is the World Bank projection. Our projection/prediction using the logistic equation fit is shown as the green line. Note that there is relatively little disagreement between the models until 2050; the real point to discuss is whether a smooth transition to a stable world population is possible under environmental constraints.

Our analysis assumes that population continues the trend it has followed roughly for the last 45 years; similarly the more sophisticated models smoothly extrapolate present values of life expectancy and fertility. We have not considered the possibility if a sharp change in behaviour. This may be of two types. The first possible scenario is that population increases much faster and further than we project: the demographic transition that is confidently predicted for all countries of the world with high birth rates may not occur; an increase in political stability or a failure to improve child mortality may lead to a cultural ethic that continues to favour large families.

[1] Projection is generally used to refer to a future prediction of population, while estimate is used to denote data for past populations. The considerable uncertainties in the data and in using this to make forecasts preclude the use of more robust wording, such as population values and prediction.

Furthermore, the lower-than-replacement fertility observed in developed countries may prove to be a transitory phenomenon: if women are assured of a long, healthy, prosperous life and career opportunities even if they take a break to have children, exercising the option of taking 15 years to raise a large family may seem a worthwhile lifestyle choice that does not necessarily compromise a career or financial security.

The second, and much more worrying possibility, is that population growth will be limited by environmental factors – the combined effects of over-farming, population increases and climate change mean that we are unable to grow sufficient food to support the population. Even a partial realization of the horror in Rwanda or other countries that have suffered a transitory drop in population through conflict or famine should be sufficient to motivate anyone to avoid this catastrophe. I am certainly not going to speculate on what might happen, but this will be mentioned again briefly later.

In conclusion, the best and most effective way to achieve a stable, sustainable population is not through increasing the death rate (note that two world wars and the death of millions in China and Russia this century while it did, briefly, decrease the rate of population growth never led, overall, to a decrease in global population), but by decreasing the birth rate.

3. Oil

In this chapter, I will do my own – characteristically simplistic – analysis of oil reserves as my contribution to the now widespread debate on ‘peak oil.’ I will start with a simple analysis of the future of oil production using the logistic population balance model introduced in the last chapter. Indeed, it transpires that armed with no more than a simple equation, I can make predictions of all sorts of important things. Only time will tell if I am right…

In 1962, M King Hubbert, a distinguished hydrologist, wrote a report on the future of US energy. In it he predicted future US oil production with startling accuracy — it is probably the most accurate economic forecast ever made. He correctly predicted that US oil production would peak in around 1975 and then decline. His prediction of ultimate US oil production is also in line with current estimates. I will review the King Hubbert analysis for US oil production and then make my own prediction for global oil production. Before we start, let's consider a few key points:

1) Oil is a finite resource. Therefore the total amount of oil that will be produced is finite.
2) Oil production started at some time in the past (1859 in the US, 1857 in Romania).
3) Initially oil production underwent almost exponential growth, as new discoveries prompted more exploration which prompted more discoveries and so on.
4) In view of 1), oil production must peak at some time and then decline.

Exponential growth and the logistic equation

Let’s return to Eq. (10) in the last chapter. As it is central to the analysis here, I will rewrite it:

$$g = \frac{1}{P}\frac{dP}{dt} = r\left(1 - \frac{P}{K}\right) \tag{12}$$

Can we use the same equation to describe the rise and eventual fall of oil production? Is there an analogy between population growth and oil production?

Symbol	**Population biology**	**Oil**
N	Population	Cumulative recovery
ΔN	Increase in *N* in 1 generation	Oil production
r	Growth rate	Growth in production rate
K	Carrying capacity	Total oil ever recovered

To apply this analysis consider US oil production up to 1960 (essentially the data that King Hubbert had when he made his predictions). For all the data on oil production in this chapter I am using the BP Statistical Review of Energy.

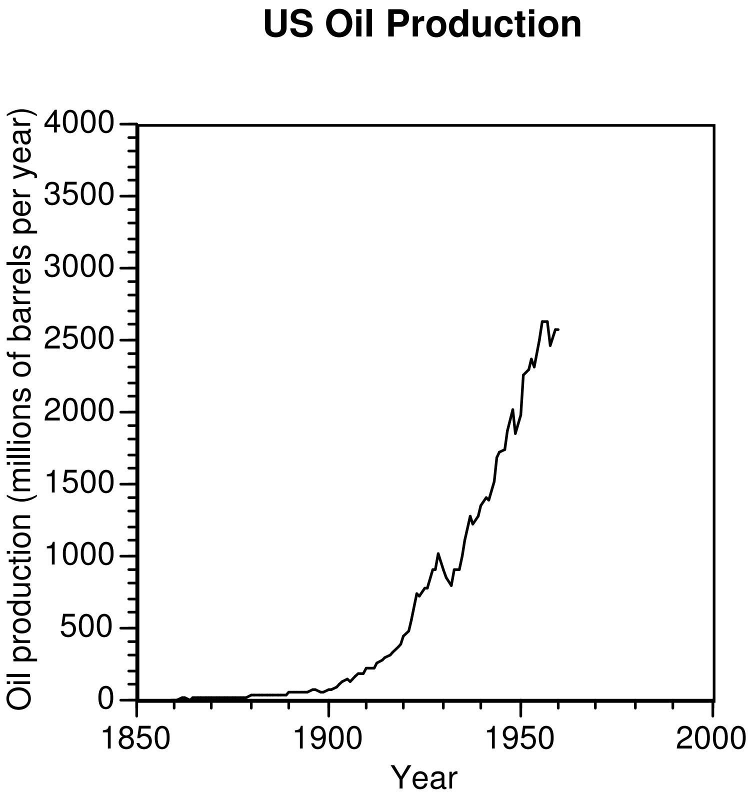

Figure 14. US oil production until 1960. Note the seemingly inexorable rise, which fuelled unprecedented prosperity.

Before we continue, we will redefine some terms. *P* in an analysis of oil production will always be thought to mean production; unfortunately while it readily stands for population, in oil terms it means cumulative production. No end of confusion will result. So, we will use the symbol *N* to represent cumulative production and ΔN to be the production. Second, we have hitherto considered population as a continuous variable, even though it is only estimated at specific times (every year at most). It turns out that there is a more elegant way of looking at this, implicit in the way we defined population growth rates numerically, from differences in population estimates.

Define: ΔN_t = Oil production in year *t* and N_t = Cumulative oil production to the end of year *t*. The logistic equation relates ΔN_{t+1} to N_t— we write Eq.(12) as:

$$\Delta N_{t+1} = rN_t \left(\frac{K - N_t}{K} \right) \tag{13}$$

$$N_t = \sum_{i=1859}^{year\ t} \Delta N_i \tag{14}$$

So in time-honoured engineering fashion, if we plot $\Delta N_{t+1}/N_t$ vs N_t we should obtain a straight line: this is essentially what we did for population in Figure 12. When $\Delta N_{t+1}/N_t=0$, $N_t=K$. When $N_t=0$, $\Delta N_{t+1}/N_t=r$.

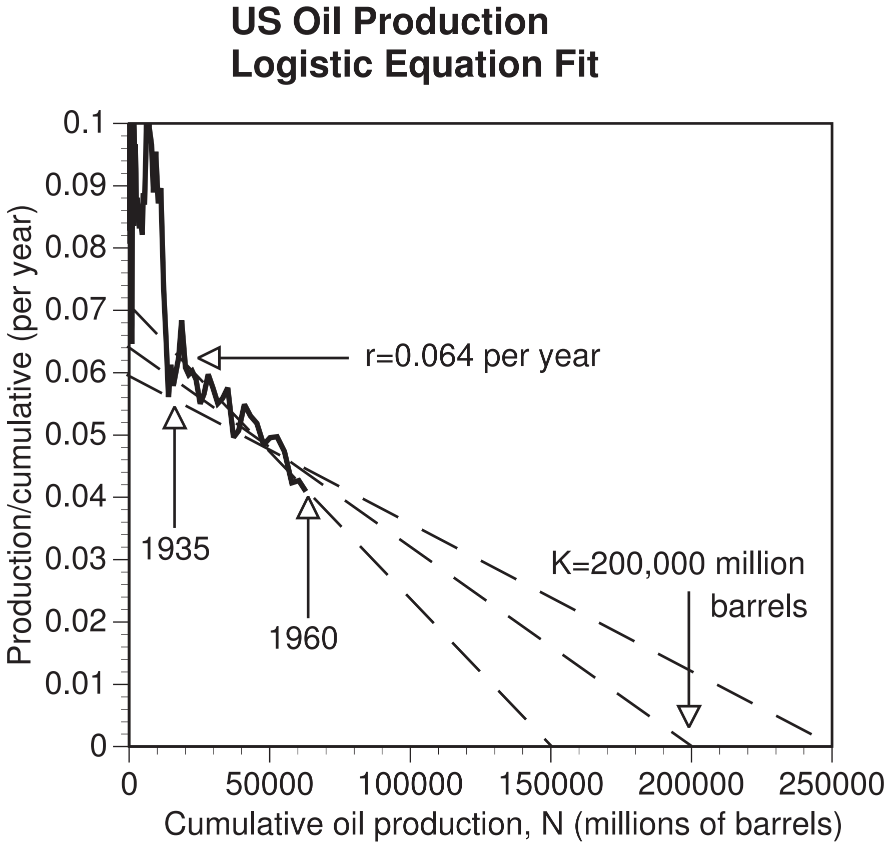

Figure 15. US oil production until 1960 and the corresponding fit to a logistic equation.

Notice that the data is a reasonable fit to a straight line after about 1935. By eye, I estimate an ultimate production of 200 billion barrels, with a possible range between 150 and 250 billion barrels. King Hubbert estimated 175 billion with a range 150 - 200 billion. I think he was rather over conservative.

How do we use our estimated values of K and r to make a prediction for oil production? Before, with population, I simply put values in a closed-form equation matched to population at some given date. Here I will do this differently in a way that does not require us to know the solution of Eq. (12). This involves some algebra though. We want to predict *production*, or ΔN. We know ΔN in 1960 and we obviously want our model to get this value correct! What we do is find the model value of cumulative production, N_t, that would give the correct value of ΔN_{t+1}. This seems confusing, but it does ensure that our predictions start with the right production.

We know:

$$\Delta N_{t+1} = rN_t\left(\frac{K - N_t}{K}\right) = rN_t\left(1 - \frac{N_t}{K}\right) = rN_t - \frac{r}{K}N_t^2 \tag{15}$$

Or:

$$\frac{r}{K}N_t^2 - rN_t + \Delta N_{t+1} = 0 \tag{16}$$

This is a quadratic equation for N_t:

$$N_t = \frac{K \pm \sqrt{K^2 - 4K\Delta N_{t+1}/r}}{2} = \frac{K}{2}\left(1 \pm \sqrt{1 - \frac{4\Delta N_{t+1}}{Kr}}\right) \qquad (17)$$

The two values of N_t are for before and after peak production – for the US in 1960 it was clearly before the peak and so we take the negative root.

In 1960, ΔN_{1960} was 2,574.81 million barrels per year. Solving for N_{1959} with K=200,000 million barrels and r=0.064 per year, gives:

$$N_{1959} = \frac{200{,}000}{2}\left(1 - \sqrt{1 - \frac{4 \times 2574.81}{200{,}000 \times 0.064}}\right) = 55{,}799 \textit{ million barrels.} \qquad (18)$$

This is the model cumulative production for 1959 to obtain the correct prediction of production in 1960. Then to find the production for 1960:

$$\Delta N_{1960} = N_{1960} - N_{1959} = rN_{1959}\left(\frac{K - N_{1959}}{K}\right) = 2{,}574.8 \textit{ million barrels.} \qquad (19)$$

Which, by construction, is correct! Our estimate of cumulative production, to the end of 1960, N_{1960} is:

$$N_{1960} = N_{1959} + N_{1960} = 58{,}374 \textit{ million barrels.} \qquad (20)$$

Then, using the same approach, you can calculate the oil production and cumulative oil production for 1961 and so on. When plotted out, the prediction shown in Figure 16 is rather good.

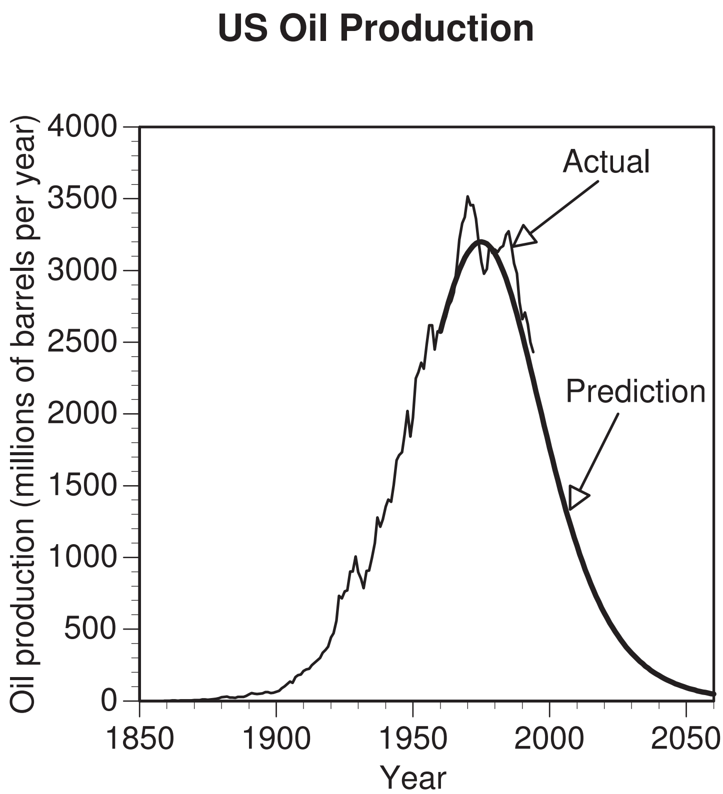

Figure 16. US oil production with our logistic equation fit.

Notice how accurate our prediction is. We estimate peak production in 1975 (it was actually in 1972) and then the beginnings of a decline. At the time King Hubbert's predictions were considered exceptionally controversial, but he has been proved largely correct. Nowadays, there is little doubt that US production will continue to decline.

If we look at the logistic equation fit, Figure 17, we see that production since 1960 has followed a straight line — this again confirms that this is a good model for estimating oil production.

It appears that we have slightly under-estimated final cumulative production *K*, which now appears to be in the range 210 — 220 billion barrels. This could be because our figures have included new production from Alaska and off-shore Gulf of Mexico. Also I have rather old data that stops in 1994. I will now consider more a more recent analysis of global oil production.

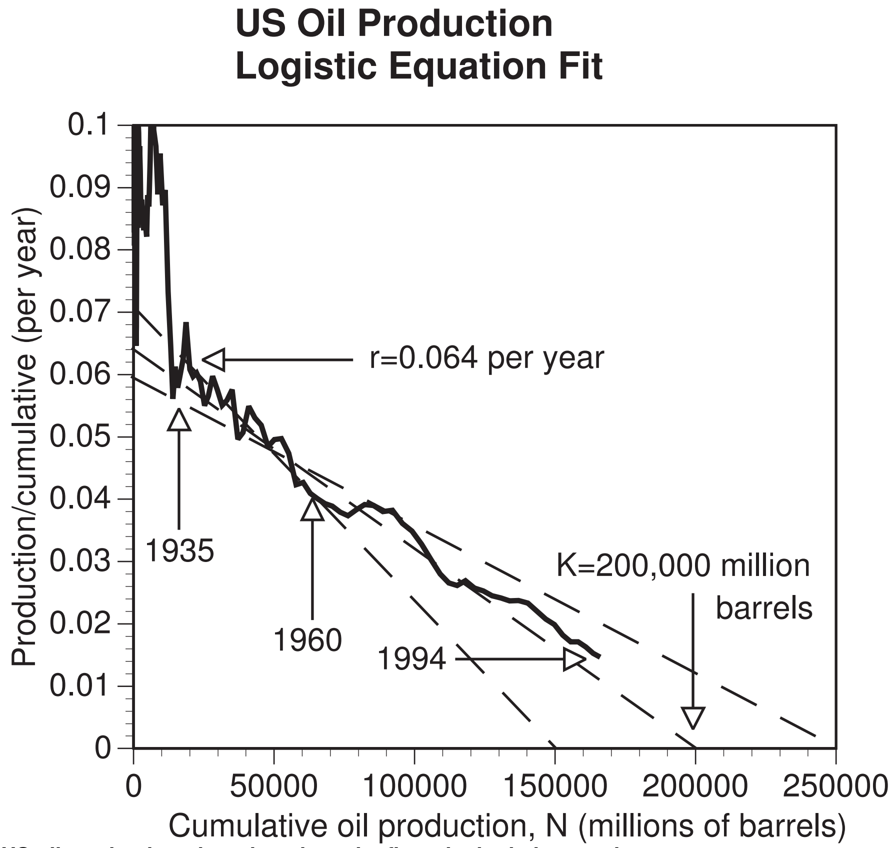

Figure 17. US oil production plotted to show the fit to the logistic equation.

World oil production

I have performed exactly the same analysis for world oil production. First I have plotted the logistic equation fit, Figure 18. The points do not lie on as good a straight line as for US oil production, but the plot has followed a convincing linear trend for the last 25 years. We will use this as our best fit, with K = 2,400 billion barrels and r = 0.050 per year.

Applying the same technique as before we use the logistic equation to predict production until 2100, shown in Figure 19. The interesting feature of this analysis is that we appear to be near the peak of expected oil production – cumulative production to date has been around 1,000 billion barrels, approximately half our predicted cumulative recovery. If this appears somewhat pessimistic, it compares well with the world's total recoverable reserves (in our analysis this is K minus cumulative production) of 1,208 billion barrels.

This is only a simplistic analysis – after all there is no good theoretical reason why oil production should follow the logistic equation. However, the predictions are not significantly different from the best geological estimates of remaining easy-to-recover oil in the world.

different from the best geological estimates of remaining easy-to-recover oil in the world.

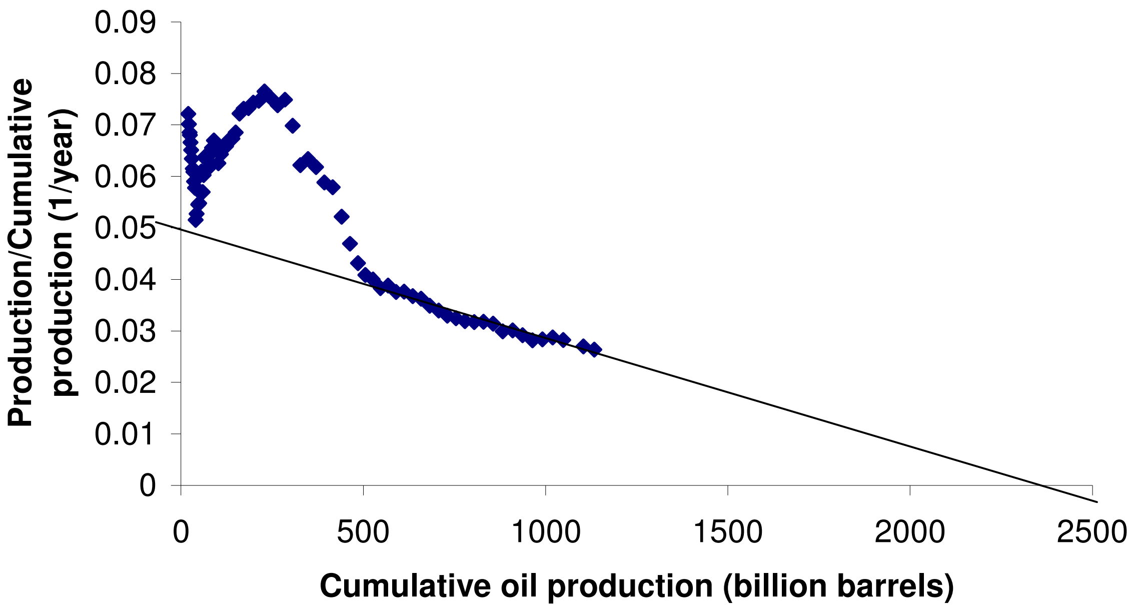

Figure 18. Logistic equation fit to world oil production.

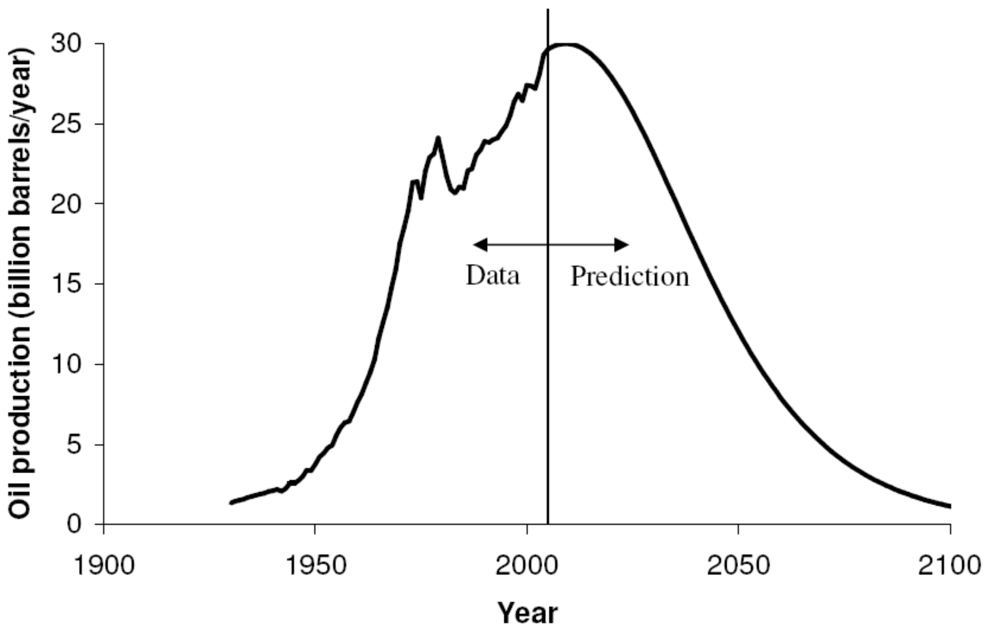

Figure 19. World oil production and prediction using the logistic equation. Peak oil is estimated to occur around 2010.

The analysis implies that in the future new technology will have to be able to produce oil that is not readily recovered at present – such as heavy oil, tar sands and oil in deep water, or alternative supplies of energy will need to be found. One thing though – we are not about to run out of oil completely – and, as it becomes increasingly scarce, improved reservoir engineering will be more and more important.

It is likely that over the next 50 years oil will be seen as an increasingly valuable and scarce resource. The present combination of rapid economic growth and relatively inefficient fuel consumption cannot continue indefinitely. There is likely to be a combination of improved fuel efficiency and a move away from oil use to other energy supplies. This may not happen significantly in the next decade, but is inevitable on a longer time frame, because of the limited supplies of oil.

Another way of looking at this is to consider that the US uses approximately 20 million barrels of oil a day and has a population of around 300 million. This is around 0.07 barrels of oil per day per person. The world in 2006 produced about 80 million barrels a day. The world population is more than 6 billion. This is 0.012 barrels of oil per day per person. If everyone in the world consumed as much oil as in the US, oil production would need to increase 6-fold and supplies would dwindle to less than ten years at this production rate. Even the most optimistic forecasts cannot accommodate such increases.

We are already seeing evidence of an impending peak in oil production: while many basins are now mature and in decline – the US, North Sea and even some parts of the Middle East – there are no new areas opening up to compensate. Estimates of increased production from Iraq and Saudi Arabia are becoming increasingly hysterical and implausible and while new discoveries are being made in Angola, Brazil and elsewhere, the size of these discoveries is insufficient to make up for consumption. The peak for discovering oil was in the 1950s and 60s (see the analyses performed by Colin Campbell and others; the reference list contains a list of some of the peak oil websites that discuss these issues at great length). We need to find an 800 million barrel field every ten days to compensate for production. A new province with reserves equivalent to the US or Saudi Arabia – around 200 billion barrels – accounts for only 6 years of consumption at present rates. No we *not* going to find a new Saudi Arabia with this frequency. We can improve recovery from fields already discovered and exploit unconventional resources, but the era of easy-to-recover conventional oil will, inevitably, come to an end. The use of non-conventional resources may help, as mentioned above, but this has implications for carbon dioxide emissions, which will be discussed in the next chapter.

I suggested class exercise is to perform your own analysis of world oil production using the most recent data and draw your own conclusions.

4. Fossil fuels and global warming

In this final chapter, I will try – very briefly – to tie up my analysis of population and oil production with a related discussion of carbon dioxide emissions and global warming.

With current concerns over possible changes to the climate due to emissions of carbon dioxide into the atmosphere, a perfectly justifiable environmentalist argument is that oil production should be curtailed not for geological or technical reasons, but because of concern over global warming. My opinion is that this is unlikely, since the limited supply of oil is more likely to become an issue in the next decades than serious environmental constraints on production. My analysis below suggests that the impact of oil and gas production on atmospheric carbon dioxide concentrations and, by inference, global warming, although negative, is not as significant as coal. Unfortunately, as the easy oil runs out, there is likely to be a switch to more carbon-intensive fuels, such as coal, with possible dire consequences for the climate.

I will now estimate by how much the atmospheric concentration of CO_2 will increase if we were to burn all the proven recoverable reserves of oil (1,200 billion barrels) and gas (181 trillion cubic metres). The estimate of gas reserves is very uncertain – generally gas reserves are generally under predicted, since gas reservoirs have little value until a market for the gas has been established. As I will be making only a rough estimate, I will assume that oil has a similar molecular composition to octane (molecular mass 0.114 kg.mol^{-1} and 8 moles of carbon per mole) and has a density 800 kgm^{-3} and that the gas is methane (molecular mass 0.016 kg.mol^{-1} and 1 mole of carbon per mole) that behaves as an ideal gas. Then the number of moles of carbon in all the yet-to-be-produced oil is:

$$(1.2\times10^{12}/6.29)\times800\times8/0.114 = 10.7\times10^{15} \text{ moles,} \qquad (21)$$

where I have used the conversion that 1 m^3 = 6.29 barrels. For gas, using the ideal gas law $n = PV/RT$, where n is the number of moles, V is the volume, P is the pressure (1.01×10^5 Nm^{-2}), T is the absolute temperature (288 K) and R is the gas constant (8.314 JK^{-1}mol^{-1}):

$$10^5\times1.81\times10^{14}/(8.314\times288) = 7.6\times10^{15} \text{ moles.} \qquad (22)$$

So the total amount of carbon produced by burning proven reserves of hydrocarbon is approximately 1.83×10^{16} moles.

What is this in terms of an atmospheric concentration of carbon (or, more specifically, carbon dioxide)? The total number of moles in the atmosphere is quite easy to calculate. From knowing atmospheric pressure and the surface area of the earth, we can compute the mass of the atmosphere using Newton's law, $F = ma$, or $4\pi r^2P = gm$, where r is the radius of the earth (6.38×10^6 m) and g is the acceleration due to gravity (9.81 ms^{-2}). From this we obtain a mass, $m = 5.2\times 10^{18}$ kg. Assuming that the air is an ideal gas with a molecular mass close to nitrogen (0.028 kg.mol^{-1}) we find that the air contains approximately 1.86×10^{20} moles.

Hence the atmospheric concentration of carbon we predict from burning the world's hydrocarbon is $1.83\times10^{16}/1.86\times10^{20}$ which is around 10^{-5} or 100 parts per million. Some of this increase will be taken up by the oceans, so the net contribution to atmospheric concentrations will be lower.

Atmospheric concentrations of carbon dioxide have increased from 280 ppm in pre-industrial times to around 385 ppm now, with a current rate of increase of approximately 2-3 ppm per year. Most scenarios of the impact of global warming anticipate a doubling of CO_2 concentrations over the pre-industrial level to around 600 ppm, or more than 200 ppm greater than today. Where will the extra increase come from? There are two principal sources – deforestation and burning coal. It is evident that unless very significant new reserves of conventional easy-to-recover oil and gas are recovered – and in the case of oil I am doubtful that this will be the case – hydrocarbons will not be the largest contributor to increases in CO_2 concentration. Of more serious concern is how to manage the transition from an economy that at present is utterly dependent on ready supplies of cheap oil to a world where oil is much more scarce and where a very significant proportion of our energy will have to come from renewable sources. My main worry – explained below – is that instead of moving towards renewables, the world instead uses a greater proportion of carbon-intensive fuels, increasing CO_2 concentrations even more rapidly than now with likely dangerous consequences for the climate and our ability to support a growing world population.

In the final two graphs, I will attempt to put some of this information together. Figure 20 combines my predictions of oil production and population. I plot the oil production per person per year. The peak was reached in 1979: huge strides in the efficiency of cars and the switch to gas (and coal) to supply electricity and heating have allowed the world to use more energy with less oil per head. However, from 2010, I propose that there will be a sharp decline in the amount of oil available per person: oil production declines while population continues to increase. I suggest that it is quite unrealistic to expect this ratio to increase: we either have to reduce our dependence on oil, or grab an increasingly large fraction of it away from poorer people who aspire to have the same oil-dependent standard of living we enjoy in the West.

The title of these notes '200 barrels left' refers to the amount of easy-to-produce oil we have remaining per person. This is our fair share of oil that has to last our lifetimes and those of our descendants. Also plotted is the nominal and real oil price; the implication is that as the amount of oil produced per person increases, the price will respond. I have refrained from putting in data for 2008 and 2009, as I have shown average prices, which have been exceptionally variable!

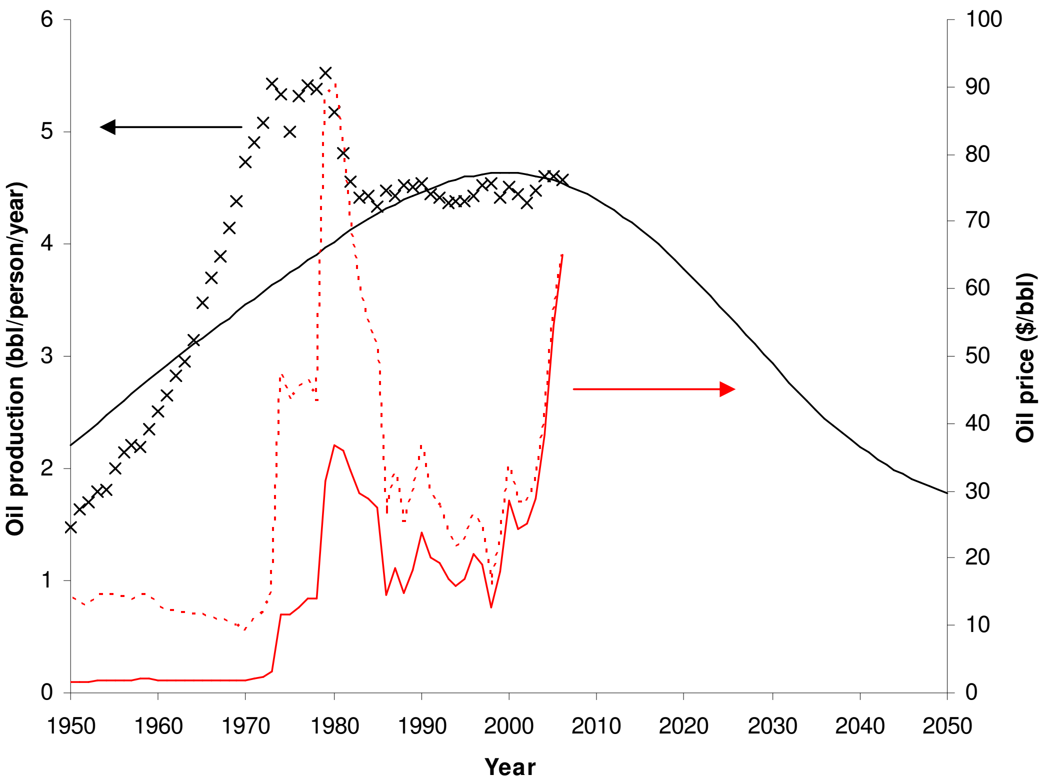

Figure 20. World oil production per person. The crosses are data and the solid line is a prediction using a logistic equation fit to both oil production and world population. Note that the production per person peaked in 1979 and that a sharp decline is predicted after 2010. In red is shown the oil price: the solid line is the price in dollars while the dotted lines show the real price measured in 2007 dollars. Data for 2008 and 2009 is deliberately left off the graph!

Figure 21 illustrates my analysis of future CO_2 emissions. I start with the CO_2 concentration before the industrial revolution, which is estimated to be approximately 280 ppm. Then, using published data, I take what we have burnt in the way of oil, gas and coal and assumed 50% ends up in the air (the other half is in the ocean). I have used best estimates for the CO_2

emitted from burning different fossil fuels, which are more sophisticated than used above. In particular, coal takes some care, as there are very different grades of coal with widely differing carbon content. The observed increase in CO_2 concentrations is consistent with measured changes in concentration. If you forget about the 50% you can show how the oil industry is culpable for the whole thing – I am surprised no environmentalist has shown this before. Actually, the oceans absorb slightly more than half the CO_2 (at present at least), I have probably over-estimated the carbon content (and fraction burnt) of the fossil fuels, but have ignored deforestation and other industrial processes, such as cement manufacture, so different errors cancel. However, the conclusion is inescapable: it is the burning of fossil fuels that has contributed principally to the observed increases in atmospheric CO_2 concentration. It is important to understand at least the basis of this calculation and that is why I stepped through the analysis for oil.

Using data from the BP Statistical Review of Energy it is possible to work this out for yourselves, and I recommend that you do. I have deliberately not given all the references here – a little hunting on the internet is sufficient to locate all the data you will need.

What about the future? I already have a Hubbert-like prediction of future oil prediction that I can convert into likely CO_2 concentration in the atmosphere. Using the BP data, I have also performed a Hubbert fit to coal and gas. This is less convincing than for oil, but a reasonable match to recent production can be made under plausible assumptions. Again, I will not give all the details, as this is something you can readily do for yourselves. Coal though is particularly worrying: consumption increased almost 6% in 2006, driven mainly by the economic expansion of China, who is fuelling their economic growth principally with fossil fuels. The global reserves of coal are huge and dwarf that of oil and gas – the default is that we will simply burn this, as oil and gas become more scarce or more expensive. Coal can also be converted into fuel oils – albeit at a high price – and so as long as there is any type of fossil fuel, we can produce the energy we need in the form we need it. The predicted oil, gas and coal production is converted into CO_2 concentration. Now, the oil industry is no longer the villain – it is coal that we have to stop using. The bottom line is that oil and gas use may be resource-constrained, but there is plenty of coal and unconventional oil.

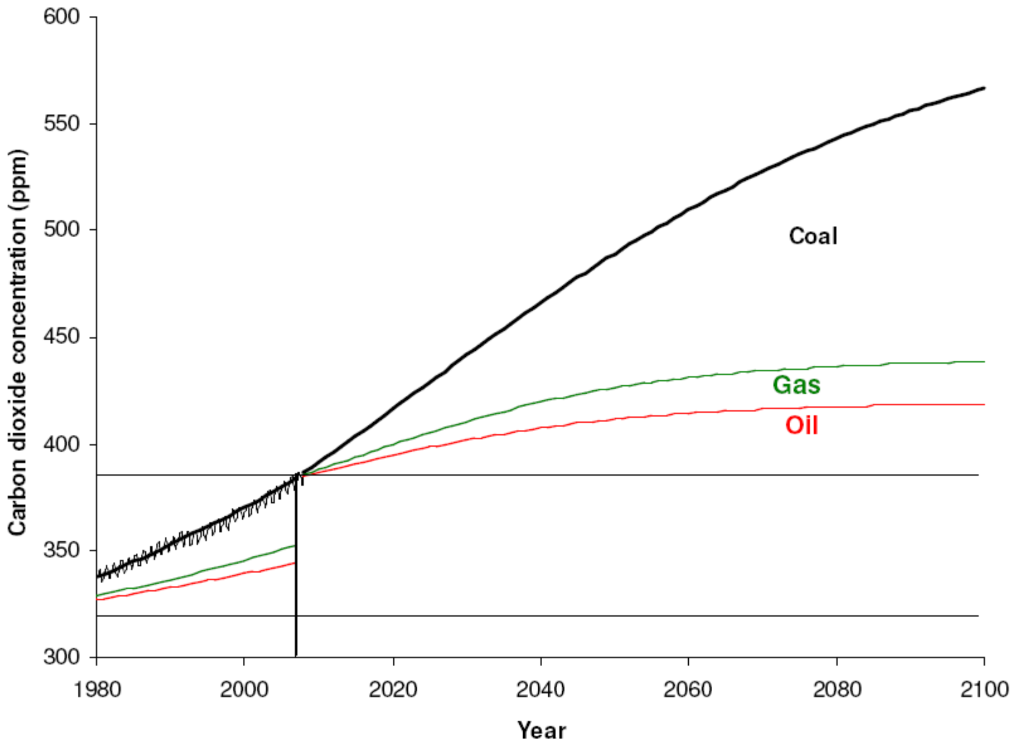

Figure 21. Predicted and measured atmospheric carbon dioxide concentrations. The wiggly solid line from 1980 to 2008 is the concentration measured in Hawaii (can you tell me why it oscillates – albeit with a rather obviously increasing trend?). The solid line is a prediction based on possible future use of fossil fuels. The coloured lines indicate the contributions of oil, gas and coal.

To recap, my conclusions are as follows, but I invite you all to perform your own analysis and make your own minds up.

1. World population in the last 45 years has approximately followed a logistic growth model, with population reaching a stable maximum of around 10 billion. This is in line with more sophisticated estimates.
2. Oil production for the last 25 years has also followed a logistic model which predicts peak production in around 2010. It is unlikely that major new discoveries will substantially change this prediction and that any increases in production need to come from improved recovery from existing fields of the exploitation of unconventional oil, such as oil sands.
3. The observed rise in atmospheric carbon dioxide concentration since the start of the industrial revolution is consistent with estimates of oil, gas and coal consumption.
4. Fitting past production of fossil fuels to a logistic or Hubbert-type model, predictions of future atmospheric carbon dioxide concentration can be made. By 2100 the concentration will be over 550 ppm in a range that most analysts believe will result in serious consequences for the climate. There is a switch from dwindling oil supplies to coal, with a consequent increase in the carbon intensity of fuel use. Exploitation of unconventional oil will also result in accelerating carbon dioxide emissions.
5. If we are to continue to enjoy a high standard of living while avoiding dangerous climate change, we need to use energy more efficiently, move rapidly from fossil fuel use to renewables (and possibly nuclear power) and capture and store the carbon dioxide that is emitted from fossil-fuel burning power stations.

And my last word, related to point 5. I will discuss carbon capture and storage in lectures, but these notes give some of the reasons why this is now my principal research interest.

References and Notes

The data I used for the prediction of global oil production, and several of my other numbers, come from the BP Statistical Review of Energy: http://www.bp.com/centres/energy/

Other information, mainly on global warming, comes from: *Climate of Hope: New Strategies for Stabilizing the World's Atmosphere*, by C Flavin and O Tunali, Worldwatch Institute, 1997.

Also interesting for background reading is *State of the World* by the Worldwatch Institute, published by Earthscan Publications Ltd, London.

Population

US Census Bureau: http://www.census.gov/ipc/www/idb/worldpop.html accessed 15th February (2008a).

US Census Bureau: http://www.census.gov/ipc/www/worldhis.html accessed 15th February (2008b).

US Census Bureau http://www.census.gov/ipc/www/idb/summaries.html accessed 11th March (2008c)

US Census Bureau: http://www.census.gov/prod/2005pubs/06statab/pop.pdf accessed 11th March (2008d).

UN Division of Population: http://www.un.org/esa/population/unpop.htm accessed 15th February (2008).
However, I was not able to obtain the same estimates of population quoted as being UN figures by the US Census Bureau.

McEvedy, C and R Jones, 1978, "Atlas of World Population History," Viking Penguin, New York, pp. 342-351.

K Blaxter, “People, food and resources,” Cambridge University Press, Cambridge UK. (1986).

J-N Biraben, Essai sue l'évolution du nombre des hommes, Population (Paris) 34(1), 13-25 (1979).

J D Durand, Historical estimates of world population: An evaluation. Population and Development Review **3**(3) 253-296 (1977).

M Kremer. Population Growth and technological change: One million B.C. to 1990. Quarterly Journal of Economics **108**(3) (August) 681-716 (1993).

M Livi-Bacci, "A Concise History of World Population," 4th Edition, Blackwell Publishing, Maden, USA (2007).

J E Cohen, "How Many People Can the Earth Support?" W W Norton and Company, New York (1995).

http://cdiac.esd.ornl.gov/ftp/ndp030/CSV-FILES/global.1751_2004.csv

Marland, G., T.A. Boden, and R. J. Andres. 2007. Global, Regional, and National CO_2 Emissions. In Trends: A Compendium of Data on Global Change. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., U.S.A

Swedish Statistical Office (2008) www.scb.se/BE-EN, accessed 11th March 2008
http://en.wikipedia.org/wiki/House_of_Saud accessed 11th March 2008
http://www.state.gov/r/pa/ei/bgn/2861.htm US State Department accessed 11th March 2008

D McMurray, Recent Trends in Middle Eastern Migration, *Middle East Report*, No. 211, Trafficking and Transiting: New Perspectives on Labor Migration. (Summer, 1999), pp. 16-19. http://links.jstor.org/sici?sici=0899-2851%28199922%290%3A211%3C16%3ARTIMEM%3E2.0.CO%3B2-A

Peak Oil
Association for the Study of Peak Oil (ASPO)/energyshortage.com.
http://www.energiekrise.de/e/index.html

The Coming Global Oil Crisis
http://www.oilcrisis.com/

Dieoff.com
http://www.dieoff.com/

Energyresources List Archives
http://groups.yahoo.com/group/energyresources/

Health and Energy/Oil Crisis
http://healthandenergy.com/oil_crisis.htm

M. King Hubbert Center for Petroleum Supply Studies
http://hubbert.mines.edu/

Oil Depletion Analysis Centre (ODAC)
http://www.odac-info.org/

Oildepletion.org
http://www.oildepletion.org/roger/index.htm

Oil Depletion Resource Page
http://www.gulland.ca/depletion/depletion.htm

M. King Hubbert. "Energy from Fossil Fuels." *Science* **109** (February 4, 1949), pp. 103-109.

http://www.oilcrisis.com/hubbert/science1949/

M. King Hubbert. *Energy Resources: A Report to the Committee on Natural Resources.* Washington: National Academy of Sciences-National Research Council, 1962.

M. King Hubbert. "The Energy Resources of the Earth." *Scientific American* **225** (September 1971), pp. 60-70.

http://www.oilcrisis.com/hubbert/energypower/

C J. Campbell and J H. Laherrère. "The End of Cheap Oil." *Scientific American* **278** (March 1998), pp.78-83.

http://dieoff.com/page140.pdf

P A. Kharecha and J E. Hansen, Implications of ‘‘peak oil’’ for atmospheric CO2 and climate, Global Biochemical Cycles, **22**, GB3012, doi:10.1029/2007GB003142, 2008