The Sustainability of Human Populations: How many People can Live on Earth (OPT website version)

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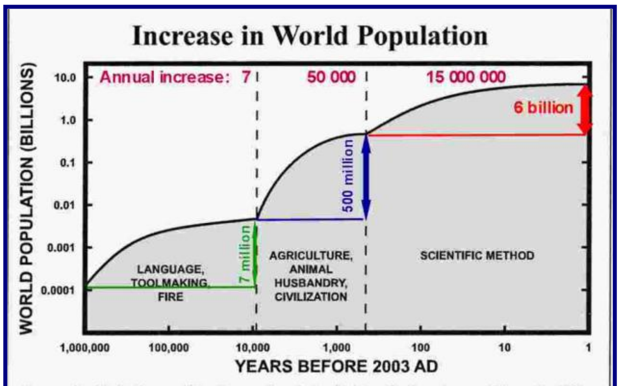
Introduction

There is nothing new about the relationship between population size and land. As early as 470 BC, Plato asserted that *'A suitable total for the number of citizens cannot be fixed without considering the land…'* The Greeks, for all their knowledge at that time, could not even begin to conceive of the vast tracts of land that existed for human exploitation. They were therefore justifiably concerned about the sustainability of their population by their limited view of what was available to them. Today, when we have come to know more fully the extent of the world and its carrying capacity, it seems that many people may have lost sight of Plato's wisdom. This paper sets out to place the current world population trends in the context of '*considering the land*'. But first, a bit of history.

A Brief History of the Impact of Human Development

In 1961, E.S. Deevey published a graph (reproduced with embellishments in Figure 1) to illustrate how the world population had grown over the last million years. By plotting them on logarithmic axes, the data show up three major phases.



Source: See E. S. Deevey, "The Human Population," *Scientific American*, v. 203, no. 3, 1960, p. 194-204.

Figure 1

The first phase relates to the prehistoric hunter-gatherer period (which includes human *homo sapiens* from about 150,000 years ago), during which the population is estimated to have grown from the order of 100,000 to around 7 million over the one million years prior to 8,000 BC. Because hunter-gatherers needed large tracts of land to supply their basic needs of fuel, food and clothing, their populations were constrained by the amount of edible vegetation and animals that nature provided in a given area, as well as their limited technology to exploit it. As a result, the impact of early humans (and their forerunners) on the environment was negligible and all their resources were renewable. It is worth reflecting that prehistoric societies grew at an average of seven people per year. This startling estimate registers how close the hunter-gatherers actually came to extinction. Had the average annual number of humans who died before reaching sexual maturity been eight more, the human race would have died out around 900,000 years ago!

The second phase started around 8000 BC with what has been termed the Neolithic transformation. European and Middle Eastern peoples slowly began to develop agriculture and domesticate animals. The resulting increase in the food supply enabled the world population to grow to 500 million by 1600AD; a growth rate which was 165 times faster than in the prehistoric period. The Neolithic transformation drove the development of building, transport, irrigation & many other technologies of civilization. As a result, human impact increased, since the need for firewood and space for settlements and cropland led to increased deforestation. Furthermore, over-irrigation caused salination and soil erosion which led to desertification of large areas: notably in Africa and the Middle East.

The gradual emergence of science and its application through engineering in the eighteenth century led to the Industrial Revolution.

A detailed look at this third phase on a conventional linear plot shows the astonishing magnitude of the population change. As a result, the impact of the third phase has been the most severe. After Columbus (1492), the colonization of new lands provided more food and wealth for the European powers - creating the Third World in the process.

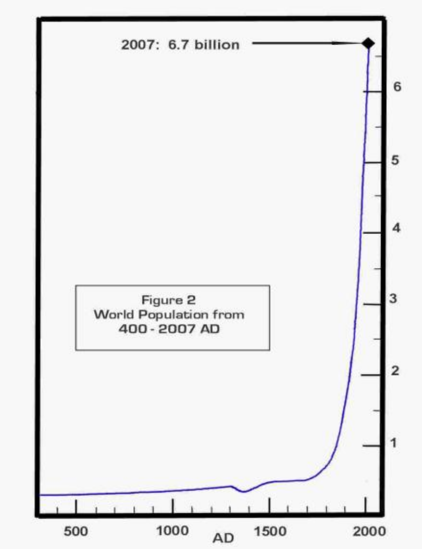


Figure 2
World Population from
400 - 2007 AD

The subsequent industrial revolution led to development of coal-fired engines, factories, more efficient agriculture and food production, as well as faster transportation between and across continents. The consequential increase in the food supply coupled with emigration to new world countries, resulted in more and larger families. The 19th and 20th centuries saw the rapid increase in inventions empowered by the exponential exploitation of coal, gas and oil. These had a positive feedback on the food supply by enabling, among many others, innovations, the production of pesticides and fertilisers and automated farming to flourish. In the industrialised world, the development of modern medicine lowered infant mortality rates and increased longevity. Inevitably, control of death without a corresponding control of birth rate caused an 11-fold explosion in population to over 6.7 billion in just 250 years. During this phase, the human population increased at an average annual rate of 15 million – 2 million times higher than the first phase of development.

Human Impact

Not surprisingly, the impact of this population growth on the environment since 1750 been extensive. Now, not a day goes by but we hear of droughts, floods, famines, wars over resources, extinctions, and in the last 20 years, the increasingly evident effects of global warming. This *impact* has been expressed in what has become known as the Commoner-Ehrlich Equation:

$$I = P \times A \times T.$$

This states that the **impac**t (**I**) on the environment is directly proportional to the population size **(P)**, the **'affluence' (A)** {defined as the resources a population consumes and wastes} and **technology (T)** through which we (1) prolong life, (2) produce things more quickly and cheaply (feeds back into consumerism and affluence) and (3) grow food faster – which feeds back into 'population'. All-in-all, this equation neatly summarises the impact of humankind on the planet.

The reality of the impact has already been mentioned: deforestation, soil erosion, salinity of the soil, waste disposal to landfill, desertification, declining fish stocks, global warming and rising sea levels and climate change. Politicians, unsure what to do, offer solutions which include suggestions such as: develop fuel efficient cars; change to efficient light bulbs; fly less; build renewable energy and nuclear power plant; increase mass transit systems; plant trees etc., etc. These solutions only address the reduction of the *Affluence* and *Technology* terms, but never the *Population* term.

Reducing impact by decreasing affluence only partly addresses the problem since populations are growing faster than affluence decreases – vide Africa, India and the Philippines. Technology does not decrease. Whilst it can be used to reduce the impact of *affluence,* it is likely that its benefits in energy saving devices will be cancelled by its disadvantages, as businesses continue to use it to maximise their economic growth via consumerism. So, realistically, *impact* will continue to rise since economic growth demands it. This is bad news since, as we will now see, human impact on the planet is already unsustainable.

Few would argue with the statement that '*population cannot continue to increase indefinitely*'. But this begs the question: "*Have we exceeded the limit?"* This question demands a reply to: *"How do we define the limit?*" A reasonable answer, I suggest, is: *"The limit of population at any given time is determined by the planet's ability to support that population's impact indefinitely."* So: "*Is the current population sustainable?"* To throw some light on this, we need to use a tool called **Ecological Footprinting** developed in the 1990s by William Rees and Mathis Wackernagel. It is now managed by the Global Footprinting Network (GFN) and publishes annually the ecological parameters for every country in the Living Planet Reports of the World Wildlife Fund (WWF). The latest of these reports appeared in 2006 and gives footprinting statistics for 2003. What follows is based on data taken from that report.

Ecological Footprinting

Biocapacity

Ecological Footprinting measures the impact of humans population on the planet. It first measures how much resource the planet generates in a year and then calculates how much we use: a biological income - expenditure account. On the income side, the total biological product over a year is called the planet's ***total biocapacity*** and is defined as the biologically productive area of land and water arising from forests, croplands, grazing lands and fishing grounds needed to:

a) produce sustainably all the biomass we use and
b) absorb all the waste we produce, including CO_2 emissions

Total biocapacity is measured in ***global hectares -*** defined as the total biocapacity divided by the total physical area generating it**.** In 2003, the earth's total biocapacity was 11.2 billion gha (Ggha). However, a more useful measure is the *biocapacity per head of population* in units of ***global hectares per capita (gha/cap).*** Called simply the ***biocapacity,*** it describes the *average* land area available to sustain each person. In 2003, since there was a population of 6.3 billion humans sharing the earth's 11.2 Ggha, the biocapacity was 1.78[1] global hectares per person.

The Ecological Footprint

Looking at the expenditure side, what we actually use per head of population is termed the ***Ecological Footprint****.* The GFN measures this on a country-by-country basis and by summing the national footprints, the global ecological footprint is found. In 2003, the world's ecological footprint was 2.23 gha/cap, which exceeded its biocapacity by 25%.

[1] *There are 2.5 acres to the hectare, so the sustainable footprint was about 4.5 acres per person.*

This *overdraft* of 25% represents the land equivalent of the energy provided by fossil fuels[2] (our inheritance) and the missing land needed to absorb our waste CO2. In other words, because all of our carbon waste cannot be absorbed by vegetation, it is being dumped into the atmosphere and causes global warming. In 2003, one and a quarter planets were needed indefinitely to sustain the population of 6.3 billion[3]. We have therefore been living well beyond our ecological income by drawing on the fossil fuel legacy which in the long term is unsustainable.

The data in the adjacent table show that the ecological footprint of the United States was double its biocapacity despite its massive land area, reflecting its high consumption of fossil fuels.[4] In contrast, Africa's ecological footprint of 1.1 gha/cap was sustainable, being lower than its biocapacity (1.3 gha/cap) due to a very low fossil fuel usage. A further contrast: the UK's footprint is 3.5 times greater than its biocapacity, reflecting both its high population density and affluence. If the whole world consumed and generated waste like he UK, it would require 3.5 (i.e. an *additional* 2.5) planets to sustain the human race!

ECOLOGICAL FOOTPRINTS
(Taken from WWF Living Planet Report 2006)

	Biocapacity (gha/cap)	Eco-footprint (gha/cap)	Overshoot ratio
WORLD	1.78	2.23	1.25
USA	4.7	9.6	2.04
AFRICA	1.3	1.1	0.85
U K	1.6	5.6	3.50

TABLE 1

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Sustainable Population Hyperbolae

At the sustainability limit, the relationship between population and the biocapacity is a hyperbola and this suggests a novel graphical way of presenting footprint statistics.

Consider the 11.2 billion global hectares total biocapacity mentioned earlier. When it is divided by the population 6.3 (expressed in billions) it yields the world's biocapacity of 1.78 gha/cap. At the sustainability limit, the total ecological footprint is equal to this 11.2 billion hectares of biocapacity. Thus, at the limit of sustainability, the relationship

population (P) x *mean per capita ecological footprint* (F_m) = *total biocapacity* (B_t)

holds true. P is therefore inversely proportional to F_m ; the larger the population, the smaller the sustainable footprint and vice-versa. Thus, for the *world*, the equation

$$P \times F_m = 11.2$$

[2] It should be noted that fossil fuels are not included in GFN's *biocapacity*, which is a measure earth's biological resources which are generated in a 12 month period. Fossil fuels are the stored legacy of biological activity of bygone eras from around 200 million years ago.

[3] The carbon component of the world footprint was 1.06 gha/cap which means that, without fossil fuels, the world would have been living sustainably at 1.17 gha/cap instead of 2.23 gha/cap in 2003, but at a lower comfort level in the developed world.

[4] . A serious effect of global warming will be a reduction of the earth's total biocapacity through shrinkage of productive land area due to rising sea levels, storms, droughts, floods and deforestation

is an hyperbola in which P, F_m and 11.2 are expressed in units of *billions*, *global hectares per capita* and *billion global hectares* respectively. This relationship plotted in Figure 3 on a graph with population on the vertical axis and *Hyperbola* shows the maximum indefinitely-sustainable mean ecological footprint of a population. It expresses that if a population is sustainable, its footprint will plot on or below the curve. If the population is unsustainable, the footprint will plot above the curve.

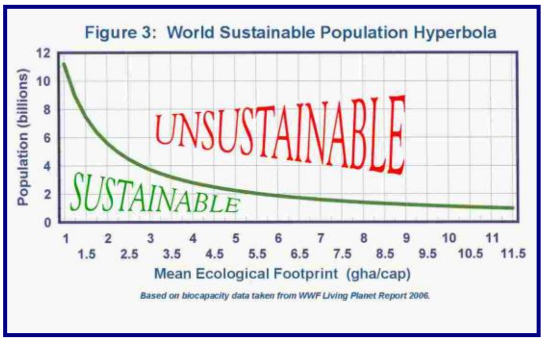


Figure 3: World Sustainable Population Hyperbola

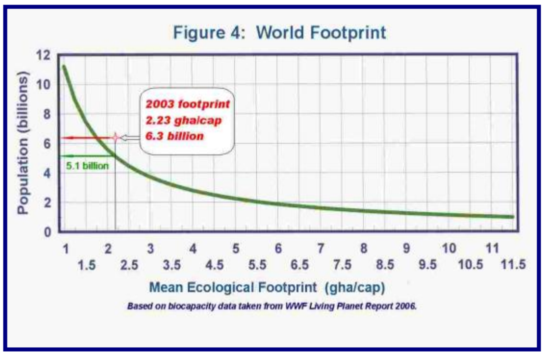


Figure 4: World Footprint

Plotting the world's mean ecological footprint[5] (2.23 gha/cap) against its population (6.3 billion) in Figure 4 shows that the footprint lies above the hyperbola: the population is therefore ***unsustainable***. It can easily be seen that an footprint of 2.23 gh/cap will only sustain 5.1 billion people.

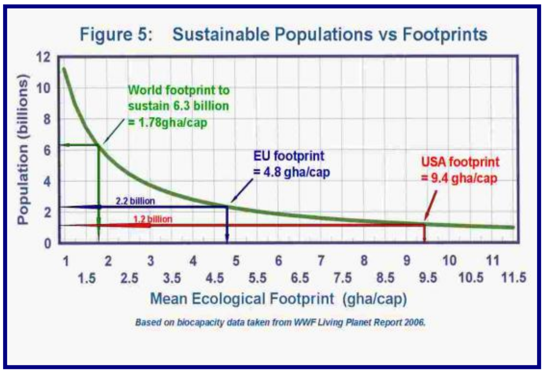


Figure 5: Sustainable Populations vs Footprints

Plotting various national footprints on the World sustainable hyperbola (Figure 5) is instructive. For example, if everyone lived with an average EU lifestyle of 4.8 gha/cap, then Earth would sustain only 2.2 billion people; an American lifestyle at 9.4 gha/cap could only sustain 1.2 billion. Such values are far in excess of the 2003 world biocapacity of 1.78 gha/cap and they emphasise that the developed world only enjoys its affluence because the people in the third world have a much lower footprint.

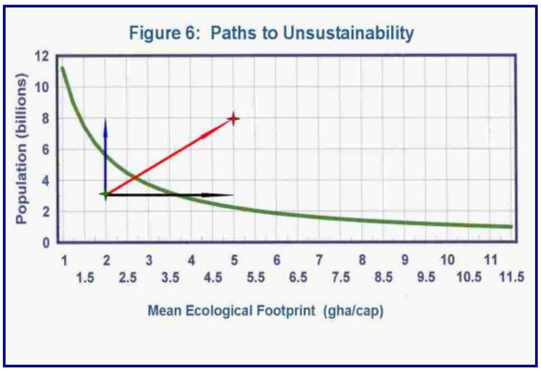


Figure 6: Paths to Unsustainability

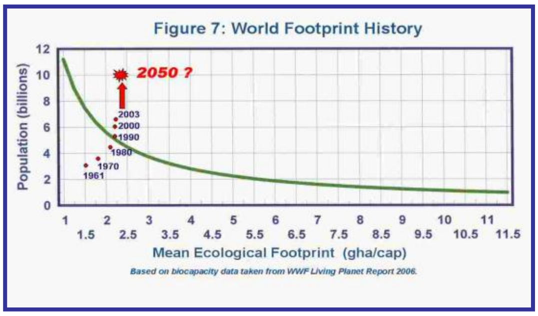


Figure 7: World Footprint History

Such hyperbolae demonstrate how the population and affluence combine to magnify the global footprint. Consider a sustainable population of three million with a footprint of two gha/cap (the green star in Figure 6). In general, any pathway to unsustainability comprises two components. At one extreme we can increase the population (blue line) from, say, three to eight billion keeping the footprint value constant and resulting in a ~35% population overshoot[6]. Alternatively, the footprint of a stable population can increase from, say two to five gha/cap (black line), resulting in

[5] Referred to hereinafter as 'footprint'
[6] 'Overshoot' is calculated by dividing the total 'variable' by the sustainable 'variable' , where *variable* in the above stands for *population* or *mean ecological footprint*

an overshoot of ~40%. However, when a combination of both applies, as it does in reality, we obtain the more drastic cumulative result shown in red. The footprint overshoot arising from the combined effect of population and affluence growth in this case is 260%. This demonstrates the amplification of overshoot when a growing population increases its per capita impact on its environment.

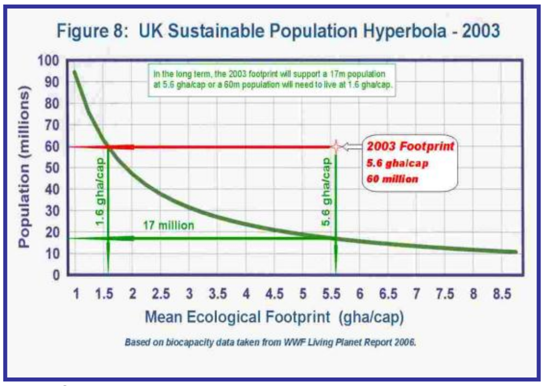
Tracking the World Footprint

GFN world data go back to 1961 (Figure 7) when the population of three billion resided firmly in 'sustainable space' with a mean footprint of 1.5 gha/cap. Between 1980 and 1990 it crossed the sustainability limit and, by 2003, had progressed into 'unsustainable space'. Until 1990, the path into unsustainability was due to a combination of increasing ecological footprint and population. After 1990, however, population increase became the driver towards further unsustainability; the path stops moving to the right and progresses almost parallel to the population axis. This appears to be because increases in population have been predominantly in poor countries with low footprints. So the average footprint is being held steady due to low-end weighting. But because the world population continues to increase, the overall footprint becomes less sustainable.

The UN predicts that by 2050 the world population will exceed 9 billion. If this happens, then combined with increased affluence (as e.g. the footprints of China and India expand rapidly) the world footprint could rise to around 2.7gha/cap. Without a serious international attempt to bring the world population back towards sustainability, the earth will become increasingly depleted of biological resources and will require humanity to conform to a reduced average footprint of 1.2 gha/cap. Because rich nations will not want to reduce their comfortable lifestyles significantly, this predicts an enormous increase in poverty and an incipient catastrophic population crash in the poorer nations. Superimpose on this scenario the impact of the predicted effects of further global warming and that outcome begins to look like a certainty. It is the author's view that the prediction of 9 billion will never be realised. Instead, the price will be extensive human suffering, through resource wars and starvation.

The UK Footprint

Each country has a hyperbola constructed on its total biocapacity. We can look at the UK hyperbola in Figure 8 as an example.



The green curve is plotted using

$$P \times F_m = 0.095$$

where 0.095 is the UK's biocapacity of 95 million gha. Rounding the population to 60 million and using the UK's ecological footprint of 5.6 gha/cap, we see that the UK is deeply embedded in unsustainable space with an overshoot of 350%. Putting it another way, with its 2003 footprint of 5.6 gha/cap, a sustainable population would be only 17 million.
This means that, the UK has currently 43 million more citizens than it can sustain in the long term without relying on other countries to keep its larder stocked and to accept the global warming consequences of its waste emissions. To live sustainably, the UK

population of 60 million would be forced to live with a mean ecological footprint of 1.6 gha/cap - a level corresponding to the average living standards of China, Paraguay, Algeria, Botswana and the Dominican Republic.

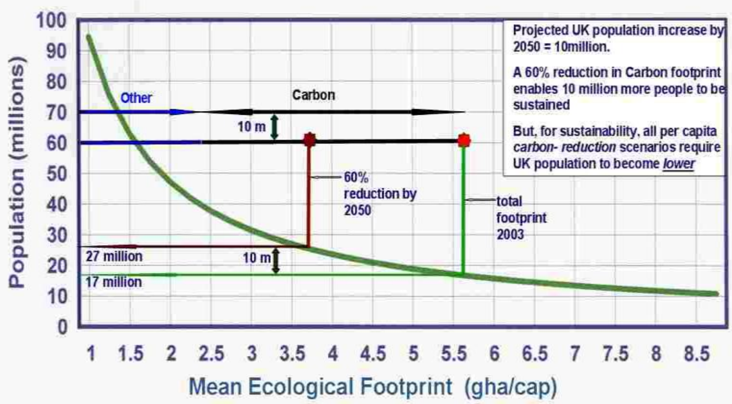
According to the GFN, the UK's ecological footprint of 5.6 gha/cap is made up from: 3.2 gha/cap attributed to carbon emissions and 2.4 gha/cap arising from all 'other' sources (Table 2). The labour government proposes to reduce carbon emissions by 60% by 2050, i.e. from 3.2 to 1.3 gha/cap. Assuming no change in the non-carbon (Other) element, the total footprint would reduce to 3.7 gha/cap. What would be the effect of such a change on UK's sustainability?

TABLE 2
UK Eco-footprint Breakdown
(gha/cap - rounded)

	2003	2050	Zero C
Carbon	3.2	1.3	0.0
Other	2.4	2.4	2.4
Total	5.6	3.7	2.4

To answer this, we refer to Figure 9 which shows the UK hyperbola with the associated footprint plotted as the red spot. The carbon footprint component is shown in black - accounting for 3.2 gha/cap - and the 'Other' non-carbon component of 2.4 gha/cap is shown in blue. As already mentioned, the total footprint of 5.6 gha/cap will only support 17 million people, but the footprint of 3.7 gha/cap, corresponding to a reduction of 60% carbon, would sustain a population of 27 million. The Government Actuary Department predicts the UK population to grow by a further 10 million in 2050[7]. The conclusion is that the government's aspirations to reduce carbon emissions by 60% - if they materialise - will only cancel out the extra growth in population and there will *still be 43 million citizens more than the UK can sustain*. Figure 9 also demonstrates that, in the highly unlikely event that the UK could reduce its carbon emissions to zero, the maximum sustainable population would need to be 40 million assuming the footprint remains constant. Therefore, even if the UK could eliminate carbon emissions, it could never reach sustainability without population reduction. The UK government needs to address this problem and put in place a population strategy which avoids any further increase in the UK population and to encourage it downwards towards 17 - 27 million, depending on far we are prepared to reduce our footprint. To fail in this task is to condemn future generations to a miserable existence.

Figure 9: Effect of reducing UK carbon emissions by 2050



Based on biocapacity data taken from WWF Living Planet Report 2006.

7 On November 28th 2007, The Daily telegraph reported that the ONS projected 'The most likely forecast based on current trends is that the population will rise to 71m in 2031 and to 85m in 2081, but if birth rates grow more quickly than expected, immigration remains high and people live longer this could reach 108 million by 2081.' http://www.telegraph.co.uk/news/main.jhtml?xml=/news/2007/11/27/npop127.xml

Such statistics make it abundantly clear that there is an urgent need for national population strategies in all countries. It is the sheer weight of human numbers that is causing the overdrawing of natural resources. If this continues uncorrected, a population crash will be inevitable. It is not sufficient to try to apply technology to solve the ‘affluence’ term in the *Commoner-Ehrlich* equation. Humans will not willingly sacrifice much of their comfortable lifestyles for the greater good (especially for people in other countries) unless it is taken from them, either by legal restrictions (such as rationing, import restrictions, taxation etc) or failing those, by nature through the misery and deprivation that must inevitably follow decades of collective overconsumption and waste. Would not a more intelligent approach would be to bring about a voluntary reduction in the population of the world while trying to constrain affluence? Such a move will not be without a set of economic consequences, but surely it would be the lesser of two evils.

Concluding Remarks and Observations

The Global Network Footprint statistics show that, globally, we left sustainability behind during the late 1980s. Since then, increasing world affluence and populations have driven us deeper into unsustainable territory. The carbon dioxide emissions of each country pollute the atmosphere for every other nation and the human urge to improve its affluence, or impact through Technology – no matter how well off it already is – is a driver that seems set to continue. It follows that if affluence and technology are not able to decrease, then the only parameter left to reduce is *population*. The ecological footprinting data analysed in this paper have given guidelines; a sustainable global population is around two to three billion people; for the UK, the figure is between 17 and 27 million. How such a goal is to be achieved is not rocket science. Spike Milligan once commented: ‘*Condoms should be worn on every conceivable occasion*’; witty, and wiser perhaps than even he realised. Updated to include modern contraceptive techniques, that quip is even more true today

Failure of politicians to grasp this nettle and lead their nations to accept the necessity of - and to provide the means to have - smaller families will be to threaten the world at large with the worst population crash in the history of humankind. Is it to much to hope that, with all the knowledge and technology at the disposal of the planet’s most intelligent species, such an outcome could be avoided?

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Author notes:
Dr Martin Desvaux is a physicist who spent the majority of his professional life directing independent research into high-temperature materials for global electrical power and petrochemical industries at ERA Technology Ltd. He spent the last eight years researching the history of human impact on the environment, ecology, demography and the viability of renewable energy systems and alternative fuels to make an impact on emissions and global warming.
He is a member of the Institute of Physics and a trustee of the Optimum Population Trust (www.optimumpopulation.org). This paper is based on a talk he delivered to the Royal Society of Statisticians (RSS) in April 2007 and a subsequently published paper in the RSS Journal: ***Significance,*** September 2007 vol. 4, issue 3, pp 102-107.

November 28th 2007