The Sustainability of Human Populations:
How many People can Live on Earth

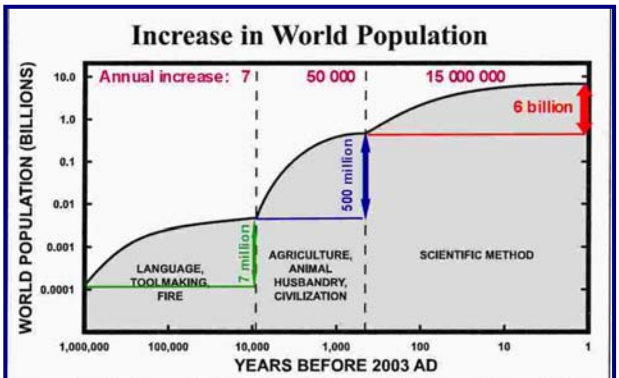
Martin Desvaux PhD MInstP CPhys

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, some history.

A Brief History of the Impact of Human Development

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



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[1] period during which the human population is estimated to have grown from the order of 100,000 to around seven 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 by their limited technology to exploit those resources. As a result, the impact of early humans (and their forerunners) on the environment was negligible as 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 gradually 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 civilisation. As a direct result of this, human impact increased, since the need for firewood and space for

[1] This includes homo *erectus* (well established by 1 million years ago) and homo *sapiens* (dating from around 100-150,000 years ago).

settlements and cropland led to increased deforestation. Furthermore, over-irrigation caused salinisation and soil erosion which in turn 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 environmental impact of the third phase has been the most severe. After Columbus (1492), the colonisation of new lands provided more food and wealth for the European powers - creating the Third World in the process[2].

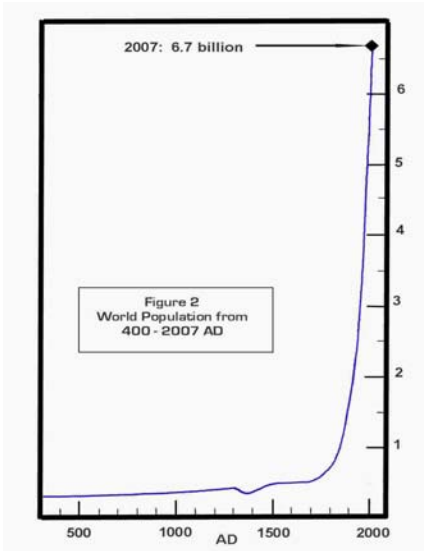


Figure 2
World Population from
400 - 2007 AD

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 has 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.

---

[2] For a thorough treatment of this topic, see Clive Ponting's book "*A New Green History of the World*"; *ISBN 978-0-099-51668-2 Chapter 9.*

The reality of the impact has been: deforestation, soil erosion, salinity of the soil, pollution, waste disposal to landfill, desertification, declining fish stocks, global warming, 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; and plant trees. These solutions only address the reduction of the *affluence* and *technology* terms, but never the *population* term.

Reducing *impact* by decreasing *affluence* (consumption) only partly addresses the problem since populations are growing faster than affluence – for example, in Africa. 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 used by the Global Footprinting Network (GFN) which publishes annually the ecological parameters for every country in the *Living Planet Report* of the World Wildlife Fund (WWF). The latest of these reports appeared in 2006[3] 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 human populations 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 available 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 stated to be 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 *biocapacity***,** this 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 therefore 1.78[4] global hectares per person.

[3] The next assessment is due in 2008.
[4] *There are 2.5 acres to the hectare, so the sustainable footprint was about 4.5 acres 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 obtained. In 2003, the world's ecological footprint was 2.23 gha/cap, which exceeded its biocapacity by 25%. This *overdraft* of 25% represents the land equivalent of the energy provided by fossil fuels[5] (our inheritance) and the missing land needed to absorb our waste CO_2. 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[6]. We have clearly been living well beyond our ecological income by drawing on the fossil fuel legacy, a situation which is unsustainable in the long term and, therefore, cannot continue.

The data in Table 1 show other examples of national footprints. The ecological footprint of the United States was double its biocapacity despite its massive land area, reflecting its high consumption of fossil fuels.[7] 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 (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 EF1f

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

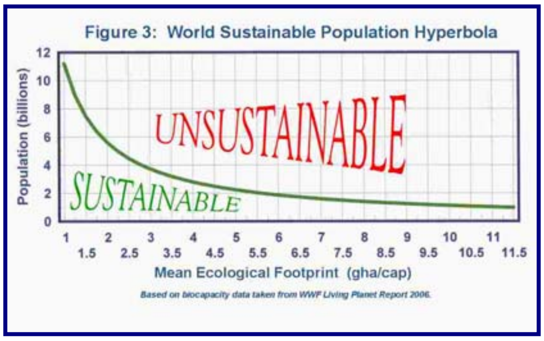
holds true. P is therefore inversely proportional to F_m; the larger the population, the smaller the sustainable footprint and vice-versa. Thus, for the world, the equation

$$P \times F_m = 11.2$$

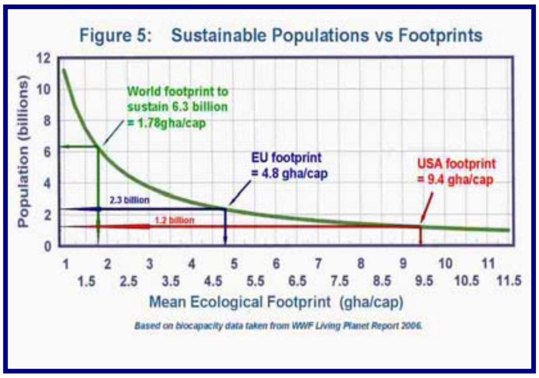
[5] For the avoidance of doubt, fossil fuels are not a part of the biocapacity. The latter is a measure of the bio-product from a prior 12-month period. In contrast, fossil fuels are the stored product of biomass from bygone eras which has, through bacterial activity over 200 million years, been transformed into a highly combustible organic hydrocarbon. It is a one-off legacy, never to be repeated in the human era.
[6] 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.
[7] . 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.

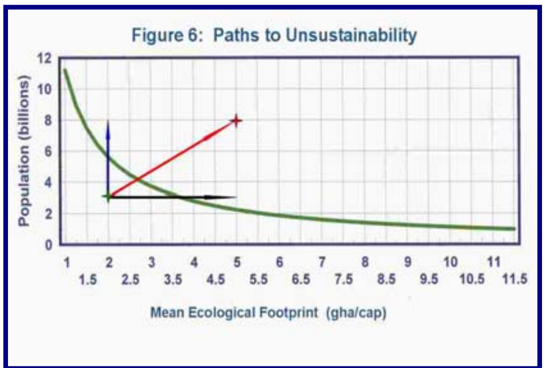


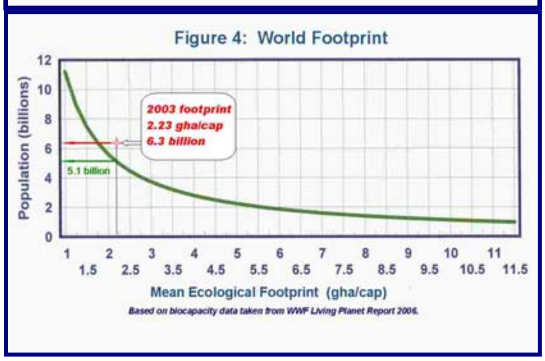
Plotting the world's mean ecological footprint[8] (2.23 gha/cap) against its population (6.3 billion) in Figure 4 shows that the footprint lies above the hyperbola: the world population is therefore ***unsustainable***. It can easily be seen that an footprint of 2.23 gha/cap will only sustain 5.1 billion people. In this way we have an immediate estimate of world overpopulation.



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 2.34 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.

Such *sustainability hyperbolae* demonstrate how the *population* and *affluence* combine to magnify the global footprint. Consider a hypothetical sustainable population of three million with a footprint of two gha/cap (represented by the green star in Figure 6). In general, any pathway to unsustainability comprises two components. On the one hand, 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[9]. Alternatively, the footprint of a stable population can increase from, say two to five gha/cap (black line), resulting in an overshoot of ~40%. However, when a combination of both applies, as has



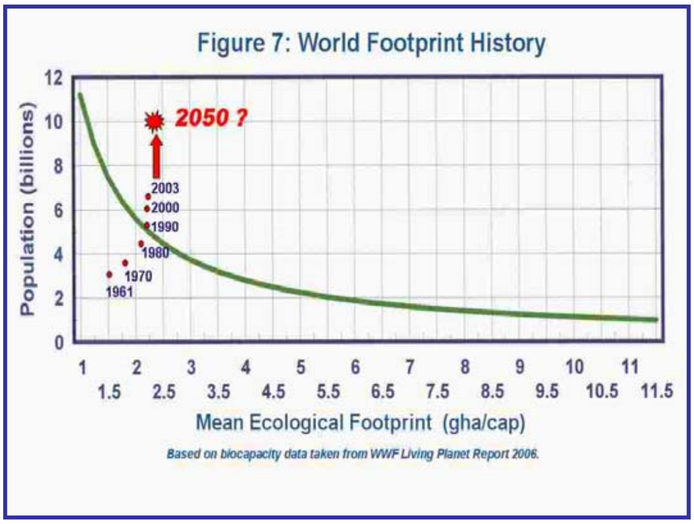


[8] Referred to hereinafter as 'footprint'.
[9] 'Overshoot' is calculated by dividing the total 'variable' by the sustainable 'variable' , where *variable* in the above stands for *population* or *mean ecological footprint*

happened in reality, we obtain the more drastic cumulative result shown by the red line. 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 effectively 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.



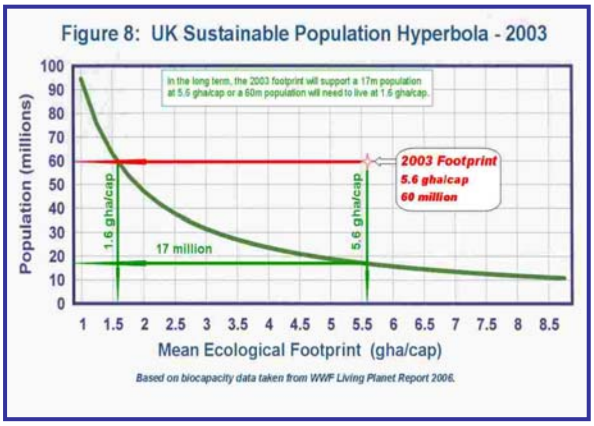
The UN predicts that by 2050 the world population will exceed nine billion. If this happens, then combined with increased affluence (as e.g. the footprints of China and India expand rapidly) the world footprint could rise to around 2.7gha/cap. Without a serious international attempt to bring the world population back towards sustainability, the earth will become increasingly depleted of biological resources and will require humanity to conform to a significantly reduced average footprint, perhaps as low as of 1.2 gha/cap, assuming no sufficiently rapid advances in, for example, food and renewable-energy technologies. Because rich nations will not want to reduce their comfortable lifestyles, 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 nine billion population 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 curve is plotted using

$$\mathbf{P \ X \ F_m = 0.095}$$

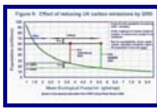
where 0.095 is the UK's biocapacity of 95 million gha with a 2003 population of 59.5 million. Rounding the population to 60 million and using the UK's ecological footprint of 5.6 gha/cap, we see that the UK is deeply embedded in unsustainable space with an overshoot of 350%. Putting it another way, with its 2003 footprint of 5.6 gha/cap a sustainable population would be only 17 million people. This means that, the UK has currently 43 million more citizens than can be sustained 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 have to live with a footprint of 1.6 gha/cap - a level corresponding to those of countries such as China, Paraguay, Algeria, Botswana and the Dominican Republic.



According to the GFN (Table 2), 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. The UK government proposed in 2006 to reduce carbon emissions by 60% from the 1990 levels by 2050. Assuming this to refer to all carbon emissions - that is, from 3.2 to 1.3 gha/cap. Assuming also no change in the non-carbon (Other) element, the total footprint would reduce to 3.7 gha/cap. What would then be the effect of such a change on UK's sustainability? [10]

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

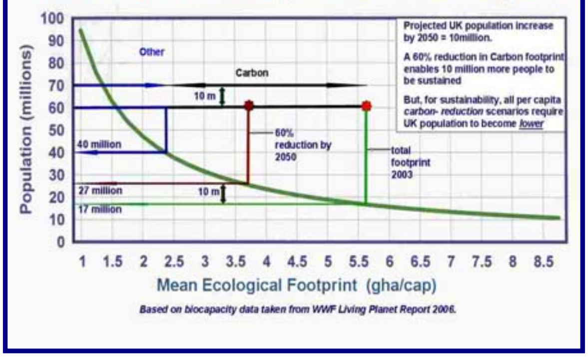
	2003	2050	Zero C
Carbon	3.2	1.3	0.0
Other	2.4	2.4	2.4
Total	5.6	3.7	2.4



[10] The forgoing assumptions, as well as the assumption that the emissions footprint in 1990 is sensibly the same as that in 2003, introduce second order approximations into the argument. However, these do not have a significant effect on the conclusions.

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 emissions, would sustain a population of 27 million. The Government Actuary Department, however, predicts the UK population to grow by a further 10 million in 2050[11]. 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 be 40 million assuming the footprint remains constant. Therefore, even if the UK could eliminate its 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



Such statistics make it abundantly clear that there is an urgent need for national population strategies in, not just the UK, but 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 neither sufficient nor realistic to try to apply technology to solve just the *affluence* term in the *Commoner-Ehrlich* equation. *Population* needs deep and urgent scrutiny; it has been avoided for far too long. Humans, from a wide spectrum of religious and political cultures, 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 or sheer force) or failing those, by nature through the misery and deprivation that must inevitably follow decades of collective overconsumption and waste in the more affluent nations. 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 have 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

[11] In October 2007, government (ONS) figures projected that the population will be 71 million by 2031 and could exceed 85 million by 2081. See: Government Actuary's Department (ONS) Population Projections

.

affluence, or *impact* through t*echnology* – no matter how well off it already is – is a driver that seems set to continue. It follows that if it is not possible to constrain *affluence* and *technology*, then the only parameter left to constrain and 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 – providing the world settles for a mean ecological footprint somewhere in the range of 3.5 to 5.5 gha/cap; for the UK, the corresponding figure works out at between 17 and 27 million.

How such a goal is to be achieved is not rocket science. Spike Milligan once commented that: '*Condoms should be worn on every conceivable occasion*'; witty, and wiser perhaps than he ever realised. Updated to include modern contraceptive techniques, his quip is even more relevant 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 *self-appointed* most intelligent species, such an outcome could be avoided?

Acknowledgement

The author wishes to acknowledge Andrew Ferguson for his helpful comments and suggestions during the preparation of this paper.

Author Notes:

Dr Martin Desvaux graduated as a physicist from London University in 1963. After obtaining a doctorate, he was appointed as a fellow of the Alexander von Humboldt Foundation and continued research at the Institut für Metalphysik in Göttingen. He went on to spend the majority of his professional life directing independent research into high-temperature materials for electrical power and petrochemical industries at ERA Technology Ltd, Leatherhead.

Since retiring, he has spent time studying, writing and giving talks on ecology, demography, the history of human impact on the environment and global warming.

He is a member of the Institute of Physics and a trustee of the Optimum Population Trust.

Publication Note:

This paper is based on a talk he delivered to the Royal Society of Statisticians (RSS) in April 2007 and subsequently published as a paper in the RSS Journal, ***Significance*** in September 2007. The definitive version of that article is available at Blackwell's.