Vol. 14: 33–41, 2014
doi: 10.3354/esep00153

ETHICS IN SCIENCE AND ENVIRONMENTAL POLITICS
Ethics Sci Environ Polit

Printed December 2014
Published online October 27

Contribution to the Theme Section 'The ethics of human impacts and the future of the earth's ecosystems'

AS I SEE IT

On the planetary capacity to sustain human populations

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ABSTRACT: This essay investigates the limiting capacity of the planet to support humans, making various assumptions about current practices and the intensities of per caput resource consumption. Supposing people to be exclusively vegetarian, consuming cereals produced by present methods, at the highest reported yields, and also eschewing the cultivation of non-edible crops, the Earth is argued to be capable of sustaining a population up to 55 billion. Consuming mixed diets including meat and beverages while continuing to raise non-food crops reduces the capacity by 7- to 10-fold, closer to the actual population at the present time. When the availability and distribution of exploitable water supplies are considered, it is difficult to argue for a sustainable population much exceeding 10 billion, without considerable changes in the equity of supply. All such extrapolations are subject to unknown consequences of rapid and chaotic climate change. The possibility that the rate of human population growth may be stabilising for other reasons, with numbers perhaps peaking at 10 to 11 billion, may yet allow increasingly widespread and severe water shortages to be avoided. This coincidence offers the opportunity to improve human sustainability through new social structures and new, cleaner, more resource-efficient technologies. They need to be directed towards solving inequities in resource use — not only of food and energy, but especially also of water. Though ultimately speculative and polemical, the essay is a genuine attempt to promote the case for recognising our real problems and the need to evolve strategies for survival.

KEY WORDS: Human ecological energetics · Cereal production · Mixed diets · Water cycles · Climate change · Equitable survival strategies

INTRODUCTION

The deceptively straightforward question that this essay addresses is: how many people can Planet Earth support? This ought to be a simple challenge, given a knowledge of the biospheric structure and an outline understanding of how planetary ecosystems function to sustain the lives of a myriad of species. Because, moreover, these processes are to a greater or lesser extent vitally integrated with the lives of our own species, *Homo sapiens*, and because (as we are at last realising) human activities so compromise the sustainability of those systems, there is now an urgency to setting and adopting policies to minimise the impact of their damage. Many people question the continued availability of sufficient clean water and secure supplies of basic foodstuffs to sustain the needs of a burgeoning human population, exacerbated by the understandable socio-economic ambitions of those people to live more fulfilled lives, based

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Publisher: Inter-Research · www.int-res.com

on better dietary opportunities. It is also clear that the resource base of agricultural land is not expanding; that there is an implicit reliance upon technology — for instance, genetic manipulation — to make up the shortfall. In addition to the challenges of population growth, food security and protecting water resources, there is the unpredictable impact of rapid and chaotic climate change. Whilst we may be able to prepare for fluctuation in the world's economic cycles — apart from our inability to wean ourselves off the habit of consuming the ultimately unsustainable fossil energy sources — and to adapt to the depletion of specific minerals and metals, we have not, so far, been able to come to terms with the scales of life support. What is the limit to population? How long is it likely to be before food or water resources run out? How can we avert it? If that is not possible, how may we deal with it? What (or even, recalling the principle of the 'balloon debate', whom) should we sacrifice first?

Already, the question is not just one of ecological energetics (though I propose to start with some basic physiology) but also one of ethics: how is it possible to accommodate what we do, what we would like to do and also to protect vital living systems (at least those bits of living ecosystems upon which we depend)?

To refine an answer to the original basic question has been a latent ambition of mine for a long time. I addressed it directly in my 'Excellence in Ecology' (EE) publication (Reynolds 1997): an elementary, energetically-based derivation was ventured but then immediately subjected to so many caveats that the outcome was quickly lost among the numerous (ethical?) possibilities. I was not, of course, the first person to attempt such a derivation — several spurious projections, based on narrow arguments, limited data or generous assumptions, collectively propose estimates of between 20 and 120 billion, the latter requiring everyone to live in tall buildings, with rooves being covered with farmland (Fremlin 1964). Quoting Taylor (1970, p. 199), these extrapolations exceed present numbers by such wide margins that they are 'morally reprehensible, as they mislead people into underestimating the problem with which the world is faced.'

Now, I have this further opportunity to rehearse and update my information. I have some trepidations about falling into the same trap, especially as I have to admit to being neither sufficiently knowledgeable nor demonstrably expert to be able to provide authoritative or credible answers to the introductory question. Even my EE book may seem not to be obviously relevant to the present problem. It set out (I thought for the benefit of the leading theoretical ecologists of the day, many of whom had grown up in the field of terrestrial plant or animal ecology) the analogies to be found among the organisms in the open water of lakes and seas: the pelagic. Water currently covers some 71% of the surface area of Planet Earth. The oceans are closely involved in the planetary exchanges of solar energy and gases of biological importance: these are central to regulating the world's weather systems. About 45% of the current annual net global carbon flux passes across the sea–air interface. Marine ecosystems are exploited extensively for the supply of food (fish and invertebrates); the dominant primary producers are the microscopic, allegedly simple, mainly unicellular plants of the plankton (microalgae and cyanobacteria) that are able, under optimal conditions, to photosynthesise, grow and double their biomass in a matter of a few hours. Their growth and rates of biomass recruitment have been very well studied, as is their fate (grazing by animals, sedimentation, mortality, etc.) and the dynamic outcomes in terms of species selection through time (see e.g. Reynolds 2006). The short time scales permit whole populations and communities to build, differentiate, undergo successional maturation and collapse, either through ageing or structural re-organisation caused by weather events. My observations led me to develop the measures of community development and to refine the concepts of its constraint by the habitat, in short, its 'carrying capacity'. Thus, we may recognise when resources are finally exhausted, how long it takes to achieve this condition and with what consequences.

My intention has been to apply this discipline to human ecology. At first, it was a relatively simple exercise to relate 'recent' (the last century or so) population growth dynamics to the capacity of resources to support them and to define the limits of sustainable growth. My initial approach has been to review how much of the planet is required to support our individual energetic needs, and then, by arithmetic division, to derive the numbers that the whole will sustain. I have to admit to some preconceptions, the same ones that I had in 1997 and oriented towards a popular belief that we are most threatened by not having sufficient food. Accordingly, I look at the energetic and material constraints on current food production and the extent to which sunlight, water supply and nutrient fertility each impinges on its supportive capacity. Then I consider our other ambitions for planetary resources, before framing ethical questions about their equitable sharing among all peoples and all species. Supposing these deductions have any validity, their sensitivity to sudden, chaotic climate variations is considered briefly. No blueprint for survival is offered but some basic components are proposed.

SOME BASIC DEDUCTIONS ON THE CAPACITY TO SUSTAIN HUMANS

Let us then consider what a human being actually needs for survival. The physiological requirements are quite wide, including space, access to air and daylight, a finite minimum of fresh drinking water (some 1.5 l ind.$^{-1}$ d^{-1})[1]. Having evolved as a hunter-gatherer, his daily food requirement is actually quite variable, typically based on opportunistic 'gorging' events separated by intervals of relative near-starvation or of modest browsing, when food encounters are rare or resources are sparse. With the development of agriculture, food harvest and storage starting only about 10 000 yr ago, a more regular food intake could become the norm; nevertheless, the fundamental nutritional requirement persists: to satisfy a basic daily metabolic rate (BMR; that required to maintain body temperature, muscle and brain function, and only in excess of which is it possible to grow and reproduce). BMR is typically stated by dieticians to be '1500 calories per day'; the 'calories' referred to are, of course, kilocalories (kcal), and following a preference for SI units (in this case the joule, J), the minimum food intake must sustain a daily BMR requirement of ~6.3 MJ ind.$^{-1}$ d^{-1}. As indicated, a 'normal healthy diet', sustaining activity levels, growth and reproduction, ideally delivers up to 2400 kcal each day, or about 10 MJ ind.$^{-1}$ d^{-1}; women require a little less (~8 MJ d^{-1}); high consumers, such as athletes and heavy labourers, and those dwelling in cold climates, may require as much as 20 MJ d^{-1}.

The energy requirement is delivered in a broad variety of foods, derived exclusively as the tissues or material stores of other organisms: cereal seeds (grain), vegetables, wet and dry fruits, shellfish, meat and fish that, together, offer a blend of carbohydrates, proteins, fats, vitamins and trace elements essential to balanced metabolism. The components complicate the calculation of how well the planet delivers the food required. In order to progress matters, I have been a little reductionist. I have first assumed that the daily dietary energy requirement is fulfilled exclusively in the form of high-quality cereal grain, for the production of which, as intensive monocultures on dedicated arable land, very good data are available. Optimal annual yields of wheat, maize, barley, oats, rye, millet, sorghum and mixed grains are collected and published by the World Bank on the internet (I used aggregates for the period 2009 to 2013 at World Bank 2013a), listed by nation and by year, and expressed in kilograms of dry grain produced per hectare of harvested land. The best national average yields are those for wheat production in Belgium, Netherlands and New Zealand, in the range of 8000 to 9000 kg ha^{-1}. The typical yields of rice in such nations as China, India, Indonesia and Vietnam are up to 7000 kg ha^{-1}. Not all the harvested seed is consumed (a portion is held back for the planting of next year's crop), neither is the yield wholly ingestible and nutritious carbohydrate. As a generous upper estimate, however, my adoption (in Reynolds 1997) of McWhirter's (1994) productive optimum of 10 000 kg ha^{-1} seems scarcely unreasonable.

The potential content of energy — more correctly, of exergy or even of enthalpy (as defined, respectively, in Mejer & Jørgensen 1979 and Atkins 2007) — of the carbohydrate available to consumer assimilation should be close to the 15 kJ g^{-1} initial investment of solar energy. This relationship determines that the mass of food required to be eaten and digested by the individual consumer in order to fulfil a daily delivery of 10 MJ is equivalent to 666 g of high-quality carbohydrate d^{-1}, or an intake of 240 kg yr^{-1}. In this way, the harvestable product of land yielding 10 000 kg ha^{-1} yr^{-1} is supposed to be capable of supporting 40 humans ha^{-1}, i.e. 4000 km^{-2}.

Now, this deduction may be compared with the total land area available. Planet Earth has a total surface area of approximately 510 million square kilometres (~510 × 10^6 km^2), of which almost 71 % is covered by ocean (~361 × 10^6 km^2). The complementary 'dry land' accounts for the remaining 29 %, or ~149 × 10^6 km^2. Compared with the human population (as I write, 7.05 billion; average population density, 47 km^{-2}), the available land area is equivalent to 21 ha per head; were this land to be raised universally to the productive level attained in Belgium or Netherlands, then we might deduce a theoretical capacity to support — (149 × 10^6 km^2) × (4 × 10^3 km^{-2}) — nearly 600 billion people!

[1]I propose to use mathematical notation and SI units preferentially; individual consumption varies with race, age, gender and especially body mass; nevertheless, the derivations here assume a mean mass of an adult male to be 60 kg. Thus, water consumption is expressed as 1.5 l ind.$^{-1}$ d^{-1}.

Plainly, this is a ludicrously optimistic and quite unhelpful deduction, primarily because so little of the earth's land surface could possibly sustain such an intensity of agriculture. Some 17.3×10^6 km^2 (12%) of the land is perennially covered by ice or permafrost; a further 33% is substantially desertified or normally experiences a soil-moisture deficit (i.e. is too arid to support productive arable agriculture). Mountain ranges and soil-free areas account for a further 20% of the land surface. Moreover, workers' homes, factories and the infrastructure of communication (roads, airports) consume land close to where its food-producing functions are needed and not necessarily only on poor-quality land. Quarrying, sand and gravel extraction and mining, naturally focussed on locations where the materials occur, are not noted for their respect of agricultural production. However, they are highly consumptive of non-physiological energy, a major part of which is generated by the controlled oxidation of fossil fuels (coal, oil, natural gas). Forests, natural and managed, cover up to 30% of the land, though some of this may well be accounted for in other categories. We have not mentioned nature reserves, where, correctly, conscience or recognition of their importance persuade us to conserve the biodiversity of species that still manage to share with us the ecosystems of the earth.

Of the productive land that can be called agricultural (48.8×10^6 km^2 in 2008, or barely one-third of the planetary land surface; FAO 2010), only 13.8×10^6 km^2 is classifiable as arable and capable of supporting intense crop production (<2 ha $head^{-1}$). Making the same assumptions about areal capacities to support humans, then the upper limit of a cereal-nourished capacity drops to 55 billion people, equivalent to a density of 511 persons km^{-2} of productive arable land. Most nations currently support population densities well short of this maximum while it can be easily exceeded in urban areas or city states (e.g. Macao supports nearly 20 000 km^{-2} and Monaco almost 19 000 km^{-2} (World Bank 2013b), obviously strongly dependent on transfers from their hinterlands; however, the dependence of the population of (say) Bangladesh (>1500 km^{-2}) upon imports is clear. Plainly, even the derivation of a planetary carrying capacity of 55 billion is grossly optimised: it leaves no room for storing reserves or cover for crop failures. Moreover, such productive intensity is not to be advocated on the basis that it so squeezes out any space for beneficial (or any) wildlife—birds, butterflies, beetles and pollinators such as bees and hoverflies, whose significant contribution to environmental services is often misunderstood, is too often underappreciated and is certainly taken for granted. Did we learn nothing from the strictures of Rachel Carson? (Carson 1962). Her work was, of course, conducted in the context of toxic dressings, such as DDT and Dieldrin, but she made clear the consequences of losing rural biodiversity. Retention of marginal land and woodland copses interlinked by hedgerows has an essential role in practical land husbandry.

The obvious caveat must be made that average cereal yields in many places are unlikely to achieve the optimum 10 000 kg ha^{-1} yr^{-1}. Thus, we have to tolerate or adapt to lower levels. We also have to accommodate the fact that, presently, many arable crops are not even grown for food — large areas are still cultivated for products such as cotton, sisal, jute, sugar and tobacco (without most or all of which, however, we really could survive) — while significant proportions of the cereal crop are fermented to produce consumable (beer) or combustible (biofuel) alcohol. Cereals are, of course, also used to supplement the diets of livestock that is then consumed as human food (meat, dairy products). Most animal protein is, in fact, derived from stock grazing of grassland, which is understood to cover everything from unimproved seasonal (savannah) and upland pasture, prairie and steppe, through to productive meadow, or the crops gathered therefrom (sileage, hay). Although nominally 35×10^6 km^2 in extent, it does not follow that grazing land is readily or necessarily at all convertible to arable land. Even were it so, the food value of secondary products, particularly of meat, consumed at a higher trophic level suffers a large (7- to 10-fold) energetic cost (a widely accepted ratio; see for instance Reynolds 1997); in other words, the land requirement of meat production sufficient to support a similar human metabolism is 7- to 10-times greater than that of direct herbivory. We could deduce that the World's capacity to support humans feeding exclusively on meat is just 5 to 8 billion. I have not included the yield from fisheries (including the important contributions of the continental shelves and the shallow African lakes), where humans 'hunt' and 'gather' an important dietary supplement to an extent greater than is good for the sustainability of the fishery (see Cushing 1996). Allowing for such over-optimisation of mixed yields from the farmable land area, their nutritive value worldwide may still be argued to be capable of sustaining a human population of around 20 to 22 billion persons consuming mainly primary products of agriculture.

CONSTRAINTS AND LIMITATIONS ON PRODUCTION

Why cannot the areal yields be improved to meet demand? Could we not simply plough up more land and grow new, genetically modified crops? Perhaps we could, but we need to be clear about physiological limitations on growth. In the end, agriculture, indeed all biological production, depends essentially on adequate insolation. Plant assimilation, growth and reproduction depend first upon the photosynthesis of carbon and water into hexose (and polymers thereof), combining with other key elements to form proteins, and ultimately, tissues. Subject always to temperature constraints, productivity usually resolves to a function of access to adequate light, nutrients and water. My own studies (substantially summarised in Reynolds 1997) led me to conclude that the photosynthetic apparatus may be sufficiently adaptable for plant photosynthesis to avoid rate-limitation down to photon fluence rates ('instantaneous light levels') of >0.1 mmol photons m^{-2} s^{-1}. Against the 'solar constant' radiation reaching the earth's atmosphere (1.36 kW m^{-2} s^{-1}) and the proportions that survive reflection, absorption, refraction and scattering by water vapour and particulates in the atmosphere, the photosynthetically-active wavelengths (about 47 % of the incoming radiation) reaching the ground under clear, dry skies may amount to 0.6 kW m^{-2} s^{-1} in the middle part of the day; the maximum visible fraction is equivalent to about 2.7 mmol photons m^{-2} s^{-1}. Low declination (around dawn and dusk, and at high latitudes) greatly reduces instantaneous light levels, as does significant cloud cover (by some 60 to 80 %). Yet almost everywhere, daytime incident light intensities still exceed the 0.1 mmol m^{-2} s^{-1}. In this way, light-limitation of photosynthesis is mainly a function of day length (the latitude-sensitive 'photoperiod') and the intensity of shade cast by other vegetation. Vegetative plant growth cannot, on average, exceed the lifetime investment of photosynthetic carbon fixation, but it is probable that, during the daylight period, fixation rates are comfortably able to saturate (exceed) the requirement to sustain growth rate.

Plant growth involves the absorption and assembly of 18 or so elements other than carbon, nitrogen and potassium, often being in the shortest supply (common salts of either being soluble and liable to leaching from topsoils) with phosphorus (which tends to be sorbed onto or complexed with metal oxides and clay minerals and, hence, not freely available). For many decades now, fertilisers have been supplied on a commercial scale to supplement soil deficiencies or to increase yields; indeed, their use has been a leading factor in underpinning the 'green revolution' of improved food-crops yield of the last 50 yr or so (see e.g. Tunney et al. 1997). Apart from the costs of winning and processing the respective 'ores' and of transporting them to their points of use, some are also in danger of falling into short supply. In the face of dwindling sources of phosphorus (quarried as crystalline apatites, typically fluorapatite or hydoxylpatite, in the USA, China and Morocco), there has been encouraging progress in the recovery of phosphorus from wastewater treatment plants (as struvite, $NH_4.MgPO_4{\cdot}6H_2O$) and in its recycling as fertiliser.

High productivity may often owe much to irrigation, emphasising a critical influence of water resources. On the one hand, water is sufficiently abundant on our earth to bestow its 'blue planet' epithet. The total volume of liquid water (close to 1.39 × 10^9 km^3) is well-conserved, but most of it (97.4 %) is oceanic and contains too high a content of dissolved salts (35 ± 3 g kg^{-1}) to be consumable by humans or be beneficial to most food-crops. The ice caps continue to store another 2 %; most of the rest is ground water. The standing volume of inland lakes and rivers (~225 000 km^3, or <0.02 % of the total, and even then not necessarily all 'fresh') is not readily exploitable either. The water we are able to use is tapped, very substantially, from the instantaneous fluxes comprising the short-term part of the hydrological cycle. To be clear, the global average annual rainfall on the land amounts to around 96 000 km^3, of which 67 000 km^3 is reckoned to evaporate before it reaches the sea (values collected and tabulated in Reynolds 1997). In other words, all terrestrial life is effectively sustained by the annual residual run-off from the land masses (~29 000 km^3 yr^{-1}, scarcely 0.002 % of the planet's liquid water). This is the scale of the exploitable resource available to humans, although in fairness, a proportion of the 67 000 km^3 is lost from terrestrial catchments as plant transpiration. Potentially, the resource available could be expanded to a very small extent by increasing the 'quarrying' of groundwater sources, and possibly by the 'harvesting' of icebergs. There are better prospects for desalination (the removal of salt from seawater) whose attractiveness has long been countered by the high energetic cost of reversing the natural osmotic gradient across a semi-permeable membrane from the dilute to the strong solution. However, the deceptively simple expedient of using natural osmosis into a still more concentrated 'draw solution' and then precipitating the new solute offers a cheap and practical alternative technique for recovering diluent from brine, and is currently under development.

Apart from the intractability of using water in obviously desertified lands of (say) North Africa, the Middle East and Australia, there are many other regions that receive some rainfall but where the ratio of resource availability to human demand is <1 and dropping, and where water has to be supplied from remote locations. These are areas of water stress, elegantly devised and mapped in a dedicated article in National Geographic Magazine (NGM 2010); they are prevalent in extensive parts of central and north eastern Asia and of western North America. In addition, there are several regions of the world where a lack of clean water and adequate sanitation seriously restricts development at all. Conversely, in a world characterised by very severely uneven distribution of water resources, the relative abundance of supplied water has been the key factor favouring both local agricultural and industrial expansion. Where demand could be satisfied naturally, water usage is probably taken too much for granted, but where, according to the same NGM graphics, it still requires over 250 000 l to make 1 tonne of steel, around 170 000 l to make a motor car, including 9000 l just to produce its tyres! About 70% of the exploitable flux that we intercept is directed first to the production of food and other biological products. To grow root or tuberous crops, such as potatoes, consumes some 300 $l\ kg^{-1}$; growing bananas takes 1000 $l\ kg^{-1}$ and the production of tree-grown soft fruits, such as plums, requires perhaps 2000 $l\ kg^{-1}$ of harvest. To manufacture a pair of denim jeans from cotton consumes about 13 000 l of water. However, raising livestock for consumption draws on still larger volumes of water. Whereas the production of chicken may account for 4700 $l\ kg^{-1}$, pig meat swallows nearly twice as much (7600 $l\ kg^{-1}$) and prime beef over twice as much again (18 600 $l\ kg^{-1}$).

There are vast disparities in the domestic consumption of water supplied directly to households in the developed, water-rich world, compared with its use in underdeveloped arid regions. Although it requires no more than 1.5 to 2.0 $l\ d^{-1}$ to keep the average person in good health, the daily consumption of water in the UK remains verifiably close to 160 to 180 $l\ person^{-1}\ d^{-1}$ (OFWAT 1999), where as recently as 60 yr ago, it averaged 'only' 49 $l\ d^{-1}$. 'Hygienic uses' (personal bathing and showers, toilet flushing, washing machines and dishwasher usage) contribute substantially to the total consumption. This water is not completely 'lost', of course — almost all the wastewater can be captured and recycled as treated water. Without this re-use, some populous areas of the UK (southeast England) would be classed as 'water-stressed'. Run-off and percolation from agricultural land is also directly recoverable, albeit often modified chemically: field drainage and farm run-off carrying inorganic residues, fertilisers and biocides or metabolic animal wastes and concentrated by evaporation are not suitable for re-use without careful processing. A large volume of the water returns to natural drainage untreated or carries pathogens and transmissible propagules of disease. Else, it is treated only inadequately, so that its organic load is only mineralised; residual concentrations of dissolved nutrients that support the growth of microorganisms (bacteria, algae) must be regarded as prejudicial to water quality, and are justifiably regarded as pollutants.

Environmental pollution is a subject on its own. As a form of short- or medium-term resource contamination likely to impinge upon human welfare, we have to be mindful of its relevance to water security. At present rates of interception, usage and under-treatment, we can infer an approximate capacity to support some 10 billion people. While demand per head continues to grow, the limiting capacity is likely to be encountered sooner and by an increasingly disaffected human population.

THE 'WILD CARD' OF RAPID CLIMATIC CHANGE

Despite the presence of a tangible, planetary, life-sustaining 'greenhouse'-like heat-retaining mechanism, recognised and named as such almost 2 centuries ago by Joseph Fourier, that was explained and demonstrated mechanistically by Svante Arrhenius over one century ago, and recent publications presenting sound and abundant evidence that it has been intensifying through the last century (when average world temperature is said to have increased by about 1°C: see the consensus of IPCC 2013), it is astonishing that there should be so many influential leaders and opinion formers, well able to assess the same factual information for themselves, who either continue to deny the gradual warming of the planet or to dismiss its relevance.

Carbon dioxide is not the only greenhouse gas, nor is it necessarily the most effective of them in its action (water vapour has a similar effect and can often be far more concentrated than CO_2, but its atmospheric half-life of a few days prior to condensing and precipitating to the surface, chiefly as rain, counters its accumulation). CO_2 is more insidious, absorbing quanta at particular wavelengths and remaining in the atmosphere, where it resides for several years. Just how many has been disputed, but the diminution in the concentration of the ^{14}C isotope relative to the more common ^{12}C in the era following the cessation of atomic weapons testings in the mid-1960s supports the estimate of about 30 yr. The overall atmospheric CO_2 content, measured directly and continuously at Mauna Loa (Hawaii) in 1958, increased from 315 parts per million (ppm; ~0.03%) to 400 ppm in 2013. Even now, the annual exchanges of respiratory carbon and the quantities withdrawn from the air by terrestrial and oceanic photosynthesis and carbonate sedimentation are in approximate balance (105 Pg C yr^{-1} in 2000; Reynolds 2006, quoting several reliable contemporaneous works). Nevertheless, anthropogenic activities (especially the combustion of fossilised deposits of biogenic carbon — coal, mineral oil and entrapped 'natural' gases and the oxidation of materials cleared or exposed in forest-clearance and land-drainage operations) have represented a small but increasing component (~7.1 Pg C yr^{-1}, although measurements of average annual increments to the atmospheric load were then 'only' about 3.3 Pg C yr^{-1}, with the balance presumed to be accumulating in the oceans). It is scarcely deniable that an altered balance in the carbon exchanges coincides with the 27% increase in average atmospheric CO_2 levels since 1958, or that these have coincided with the increase in average planetary temperature of about 1°C over this period (IPCC 2013), or to attribute any substantial part of it to the known anthropogenic enhancement of the atmospheric CO_2 concentration. This rise is associated with planetary variations in production and fertility, so far quite subtle, apart from striking changes in the extent of summer ice cover of the polar seas, particularly in the Arctic. While most people probably feel unaffected in their daily lives by a 1°C rise in temperature, it is worth recalling that natural global warming since the height of the most recent glaciation (about 25000 yr ago) has raised average temperatures by just 5°C. Possible temperature rises now (estimates anticipate 2 to 6°C over the next century or so) will not merely alter climates, crops and human activities, but are likely to profoundly dislocate present social structures and political order. The continued ability to maintain adequate and organised agricultural production within narrower latitude belts, essentially in the northern hemisphere, has to be seriously doubted.

The additional carbon is not just about cars and aeroplanes and shipping, or industry or keeping homes warmer or cooler but all of these multiplied by a growing population. The temperature rise is statistically significant, but the rate of warming has not been constant and has even slowed during the 1st decade of the 21st century. Nobody is yet certain whether this will show up as a steady feature or will rise or fall more in the future. We have yet to understand fully our ability to engineer the earth and its atmosphere.

Methane is recognised to be many (>17) times more effective than CO_2 as a greenhouse gas (fortunately it is still a much smaller component of the atmosphere). Its sources there include emission from anaerobic degradation of organic material (especially in wetlands, rice paddies and the digestive tracts of ruminants). The gas is also liberated from tundra permafrost as it succumbs to high-latitude warming: enhanced release of methane would be a positive feedback exacerbating atmospheric greenhouse gas accumulation.

Much else about the changing climate remains uncertain. What is in doubt and is persistently controversial are its proximal symptoms, and the imprecision about where and the speed with which they might be expressed. Important though these topics are, this essay does not attempt to discuss or evaluate them, merely to refer to the fact that they confound yet further the extrapolation of capacity estimates. The main concern here is the severity and stability of altered climatic patterns centred on warmer oceans and diverted currents. If the likely enhancement of differential rates of heat exchange between land and ocean masses accentuates terrestrial heating and drought, accelerates evaporation from the sea and promotes pressure differences over land, all with respect to current norms, then we may expect that the greater frequency and intensity of environmental extremes will increase and present the risk of depressing crop yields, including through incidences of flooding. Supposing the effects will be experienced at the scale of regions to subcontinents, they may well impact on the yields and onward resilience in major crop-producing areas. Without a cushion of a sufficient crop-growing capacity elsewhere, and/or an adequate reserve of products in store, food availability is lowered and, accordingly, more highly-priced in world markets. The effects generally strike most severely among poor communities, often located at some distance and where there is little alternative to going without.

Of possibly greater significance might be the long-term loss of productive land areas, although this might be compensated to an extent by an amelioration of growing conditions in lands previously excluded as being too cold or too wet. Inevitably, some translocation of population would be entailed; it would not be the first time that human re-settlement was forced as a result of climatic change, but logistically, the numbers involved next time could be very large indeed! The necessity of relocating from low-lying coastal areas and estuarine areas, forced by sea-level rises attributable to substantial melting of the polar ice caps, might be experienced directly by as much as 10 to 20% of the world's human population; that the same land areas currently fulfil a disproportionately important role in food provision is an additional complication.

OVERVIEW AND PROGNOSES

I confessed at the outset to lacking a knowledge-base or experience sufficient to be able to offer a genuinely informed, 'expert' opinion that provides authoritative or credible answers to the introductory questions on human supportive capacity, and when we will encounter its threshold. Beyond some pointers, I can draw attention to the likely problems and ideally promote a quest for more authoritative responses.

In terms of cultivating the land surface to the satisfaction of essential physiological requirements, and following the traditional philosophical approaches adopted at the beginning of agriculture about 10 000 yr ago (albeit now with vastly evolved technology), we could envisage feeding a global population of 50 to 60 billion people, provided they consumed no meat, abandoned wool or leather products, harvested no beverages, probably forewent a great deal of timber production and enjoyed a world deficient in ecosystem services. Even supposing rainfall interception, storage and irrigation adequate to sustain the envisaged cereal production, there would have to be severe restrictions on individual water consumption. Indeed, water security is probably the most imminent and precarious of the likely constraints upon future population growth. Above, I avoided pressing the upper population limit of 10 billion on the basis of current rates of consumption of water resources because groundwater exploitation and desalination still hold some potential to supplement local budgets, pending the availability of new, suitable energy sources. Tapping the present hydrological cycle, in combination with much more conservative and equable consumption rates and re-use/recycle strategies, it is not obviously capable of expanding human-supportive capacity greatly beyond its present levels.

This realisation may be surprising to many who fear an imminent population explosion, or at least the dire consequences of the natural desire to survive, but there may be some mild comfort to those who have followed the statistical extrapolations of Hans Rosling (2013)[1]. While on the one hand, our clear picture of the human population expanding from about 10 million at the end of the last ice age (10 000 yr before present) to reach its first billion by the industrial revolution (AD 1800), 3 billion by 1963 and striding on to 7 billion in 2012 fits well to the understanding of exponential increase. What has been observed at the beginning of the present century, however, is a widespread behavioural change and a declining rate of population recruitment: it has become general to raise just 2 children per couple, even in those countries where, hitherto, larger families have been typical. The current perspective is that, as earlier generations pass away, the overall population will peak anyway, at between 10 and 11 billion, possibly before serious water shortages become critical to survival.

Reference to this coincidence is not intended to engender complacency or to signal some sort of 'business-as-usual' message. Rather, we need to recognise the opportunity to promote a change in attitudes, economic structures and the intensity of material and resource demands. To continue to support a stable population should not be an end in itself, for prudence insists that it is a maximum from which a controlled retreat is essential, if there is to be any improvement in aspired living standards. Moreover, it will still be necessary to modify and better control the human dependence upon non-metabolic energy. This is now absolute, but we seem unwilling to forego the continued resort to burning fossil fuel. By no means cheap to win and transport, it is however still seen as economic and attractive to use, in spite of the deleterious and ultimately disastrous consequences of continuing to do so. The new economic fascination is with shale gas. Perhaps a determination to use the resource, not just to enrich producer nations and multinationals but seriously to invest its income into alternative, new ways of obtaining energy should be advocated; these are things we are able to do already but avoid doing so, largely on the grounds of cost of building, or the timescale of return on forward investment, difficulties of decommissioning, aesthetic considerations or popular distrust.

[1]Rosling H (2013) Don't panic – the truth about population. Production for This World Series, broadcast in UK on BBC Two, 7 November 2013.

They include geothermal exchange, nuclear power generation, well-placed wind turbines, tidal turbines in suitable locations and photovoltaic installations.

We need to progress alternative ways of meeting nutritional requirements. We might promote new foods or new ways to produce them. Algal protein, raised in well-illuminated cultures, would exploit one of the most productive yields relative to the sunlight harvested; to harness the optimum insolation rates of low-latitude deserts would not require a huge logistic effort, either in construction or product export. Synthesising muscle-like proteins from stem cells is not an altogether remote technology though it might not carry much initial appeal to consumers. We might revive the beneficial aspects of growing high-protein crops, like soya. We could expand the harvest of insect protein from cultures of dipteran larvae. We could emulate the techniques of many Asian maritime communities and grow crustaceans and bivalves on very simple detrital food sources. Were we still drawn irrevocably to meat from vertebrates, then we should accept that the returns on chicken and pigs are more sustainable than those on cattle and sheep. And the residents of rich nations should avoid over-zealous food wastage, through the triple assaults of prejudiced rejection of the foods for retail that are misshapen or miscoloured; rejection forced by the expiry of underestimated 'sell-by' dates; and the domestic disposal of food, originally purchased in excess of requirement and allowed to pass the retailers' 'best-before' cut-offs.

We need global approaches to improving economic, social and environmental sustainability, founded on cleaner and more resource-efficient technologies. They also have to address the fundamental problems of inequity in resource availability and use — not just of food and energy, but most particularly how we use water. This is easy enough for me to say but I have to accept the imperatives of taking fewer showers, eating less meat, driving and flying less, and dressing more appropriately in preference to reaching for the thermostat. And to do my best to convince several billion co-inhabitants of Planet Earth to do so too. This more respectful ethos needs to be implemented immediately.

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Submitted: April 21, 2014; Accepted: June 19, 2014
Proofs received from author(s): August 8, 2014