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Non-Renewable Resources, Sustainable Development, and Human Evolution — Short Story or Opening Chapter?

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See table of contents

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Article abstract

Humanity is beginning to grapple with the idea that the Earth is quite a small place when shared by over 6 billion people, and that the physical impact of this number of people on the planet is no longer negligible. In particular, our exponentially increasing use of energy is creating problems both in terms of supply and impact on the environment. Sustainable development has become the buzz word for solving the world's social, environmental, and ecological problems, but our understanding of what is required for true sustainability is inadequate, and does not recognize the practical limitations we face. We continue to use non-renewable resources, especially fossil fuels, as though there was an unlimited supply, with no consequence to their unbridled consumption. The slow realization by scientists and policy-makers that neither of these things is true has not manifested itself yet in any effective policy formulation on a global scale, and on a local (national, state, or provincial) scale it is largely business as usual. The writer suggests that this is because the human mind has not yet evolved to respond effectively to its relatively novel capacity for reflection on the past and contemplation of the future. We are still stuck with a psyche that is geared to look after only our own interests and those of our immediate family or social group. Our outlook urgently needs to be expanded to embrace the expedient of planning for a secure future for our species as a whole. If we wait for the natural course of evolution to effect this change, we may be too late; but if we positively engage the other human trait of willpower, then perhaps great things are possible. Geoscientists are uniquely equipped with knowledge about the history of our planet and the evolution of the species that have lived on it to inform this debate — we should not keep this knowledge to ourselves, but boldly enter the discussion.

SERIES

International Year of Planet Earth 1. Non-Renewable Resources, Sustainable Development, and Human Evolution — Short Story or Opening Chapter?

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SUMMARY
Humanity is beginning to grapple with the idea that the Earth is quite a small place when shared by over 6 billion people, and that the physical impact of this number of people on the planet is no longer negligible. In particular, our exponentially increasing use of energy is creating problems both in terms of supply and impact on the environment. Sustainable development has become the buzz word for solving the world's social, environmental, and ecological problems, but our understanding of what is required for true sustainability is inadequate, and does not recognize the practical limitations we face. We continue to use non-renewable resources, especially fossil fuels, as though there was an unlimited supply, with no consequence to their unbridled consumption. The slow realization by scientists and policy-makers that neither of these things is true has not manifested itself yet in any effective policy formulation on a global scale, and on a local (national, state, or provincial) scale it is largely business as usual. The writer suggests that this is because the human mind has not yet evolved to respond effectively to its relatively novel capacity for reflection on the past and contemplation of the future. We are still stuck with a psyche that is geared to look after only our own interests and those of our immediate family or social group. Our outlook urgently needs to be expanded to embrace the expedient of planning for a secure future for our species as a whole. If we wait for the natural course of evolution to effect this change, we may be too late; but if we positively engage the other human trait of willpower, then perhaps great things are possible. Geoscientists are uniquely equipped with knowledge about the history of our planet and the evolution of the species that have lived on it to inform this debate — we should not keep this knowledge to ourselves, but boldly enter the discussion.

SOMMAIRE
L'humanité commence à se faire à l'idée que la Terre est un endroit bien petit pour une population de plus de 6 milliards de personnes, et que l'impact physique d'un si grand nombre de personnes n'est plus négligeable. En particulier, notre utilisation en croissance exponentielle de l'énergie crée à la fois des problèmes d'approvisionnement et d'impact sur notre milieu de vie. Le développement durable est devenu l'expression à la mode évoquant la solution aux problèmes sociaux, environnementaux et écologiques de notre monde, mais notre compréhension est insuffisante quant aux mesures à mettre en œuvre pour vraiment assurer la durabilité, et nous ne réalisons pas encore les limites pratiques auxquelles nous faisons face. Nous continuons d'utiliser les ressources non-renouvelables, particulièrement les énergies fossiles, comme si elles étaient inépuisables et sans égard aux conséquences d'une consommation effrénée. La lente prise de conscience de ces limites et de leurs conséquences par les scientifiques et les législateurs ne s'est pas encore matérialisée en termes de législation efficace à l'échelle planétaire, et à l'échelle locale (nationale, de l'état ou provinciale), on continue comme si rien n'était. L'auteur suggère qu'il en est ainsi parce que la mentalité humaine n'est pas suffisamment évoluée et n'est pas encore en mesure de profiter efficacement de moyens nouveaux lui permettant de réfléchir et de tirer parti du passé et de se projeter dans l'avenir. Nous ne disposons encore que d'une psyché qui nous pousse à ne tenir compte que de nos intérêts propres ainsi qu'à ceux de nos proches immédiats et de nos groupes sociaux. De toute urgence, nous devons ouvrir notre perspective afin qu'elle embrasse les mesures de planification permettant d'assurer la survie de l'espèce dans l'avenir. Si nous attendons que l'évolution naturelle nous y amène, il pourrait bien être trop tard; en contrepartie, si nous misons sur cet autre trait humain qu'est la volonté, de grandes choses sont peut-être possibles. De par leurs connaissances de l'histoire de notre planète et de l'évolution des espèces, les géoscientifiques

peuvent éclairer ce débat - nous ne devons plus garder ces connaissances pour nous seuls, mais intervenir de manière décisive dans le débat.

INTRODUCTION

I preface this essay by stating several fundamental truths, which are probably accepted by most geoscientists but may not have wider appreciation:

- Non-renewable resources, including fossil fuels, minerals, and aggregates, exist on this planet in finite amounts, which can, therefore, be exhausted. Hence, non-renewable resource extraction is not sustainable in the long term.

- That said, as resources become scarce, their value will increase. This means that in reality, non-renewable resources will never be run down to exhaustion, but instead will simply become too scarce and expensive to exploit. Recycling, reuse, and substitution will become increasingly important.

- Large-scale human usage of non-renewable resources is a geologically and historically very recent phenomenon, its greatest development beginning with the Industrial Revolution in the 18th Century. The non-renewability of these resources relates to the timescales of human usage, and not to geological timescales. It is, therefore, a purely anthropocentric concept and problem.

- The process of extracting useful minerals and materials from ore or source rocks requires large amounts of energy, the amounts increasing as the concentration in the source decreases (i.e. lower grades). The economics of resource extraction are, therefore, critically and increasingly dependent on the price and availability of energy.

- Energy availability and affordability is likely to be the critical factor in future human development.

- Humans are but one of many species that have lived on this planet since life first appeared ~3.8 Ga ago; most of these species have lasted for only a few million years before extinction or significant evolution. There is no biological reason to think that humans will fare any differently, except that through conscious decisions, humans might be able to guide their own evolution toward a truly sustainable existence.

- And finally, when we talk about "saving the planet", what we actually mean is "saving human habitat". The Earth and its cargo of life will likely continue to thrive and evolve long after humans have quit the scene, although we have already caused the extinction of numerous species.

It is with these thoughts in mind that I approach a discussion of the topics of "non-renewable resources" and "sustainable development", with a clear understanding from the start that these concepts are relative, and defined only within the parameters of human experience and existence (i.e. they are anthropocentric constructs).

One of the most widely used definitions of sustainable development is that of the Brundtland Report of the World Commission on Environment and Development (United Nations 1987, p. 43), which defined sustainable development as "meet[ing] the needs of the present without compromising the ability of future generations to meet their own needs." This definition highlighted the need for inter-generational considerations when making decisions about resource consumption, something that is extremely difficult for humans to do because of our natural tendency to focus on our present condition. However, the fact that humans are even aware of this longer term need makes them unique in the evolution of life on this planet, because humans are so far the only species to have evolved the power of mental reflection, which allows us to evaluate the past and consider the future.

Because the topics mentioned above beg the question of the longer term future of humans (i.e. sustainable, but for how long?), I venture to argue below that developing the ability not only to consider the future, but also to make decisions that will positively impact the long-term future of our species, will probably be the next key step in human evolution. We are already the first species to have become intelligent enough to engineer our own demise, either deliberately through nuclear war, or ignorantly or selfishly through destruction of our habitat. Now our collective wisdom needs to catch up to guide these technical abilities to secure the long-term viability of the human species.

Environmentalist Jonathon Porritt provided an alternative definition of sustainability which more closely fits these goals:

> *"Sustainable development ... means, quite simply, living on this planet as if we intended to go on living here forever."* (Porritt 2002, p. 75)

NON-RENEWABLE vs. RENEWABLE RESOURCES

The term, *non-renewable resources,* is used to describe commodities that cannot be regenerated on human timescales. Thus, almost all geological materials are considered to be non-renewable, although we know that new deposits of iron, peat, carbonate, etc. are being lain down even as we speak — but too slowly to satisfy current demands. Non-renewable resources therefore include all rocks, minerals, liquids, and gases on the planet, the latter two categories including water and the atmosphere. Interestingly, clean air and water, the two most critical non-renewable resources for the sustenance of life, are among the ones we currently appear to value least, although we are beginning to see the consequences of this undervaluation in draw-down and contamination of aquifers, and global-scale changes to the composition of the atmosphere (Fig. 1).

Similarly, the term, *renewable resources,* is also a time-sensitive concept, because we know that intensive agriculture, for example, progressively depletes the fertility of the land, which must be "sustained" by adding increasing amounts of non-renewable mineral fertilizers. Renewable energy forms, such as wind, wave, and solar power,

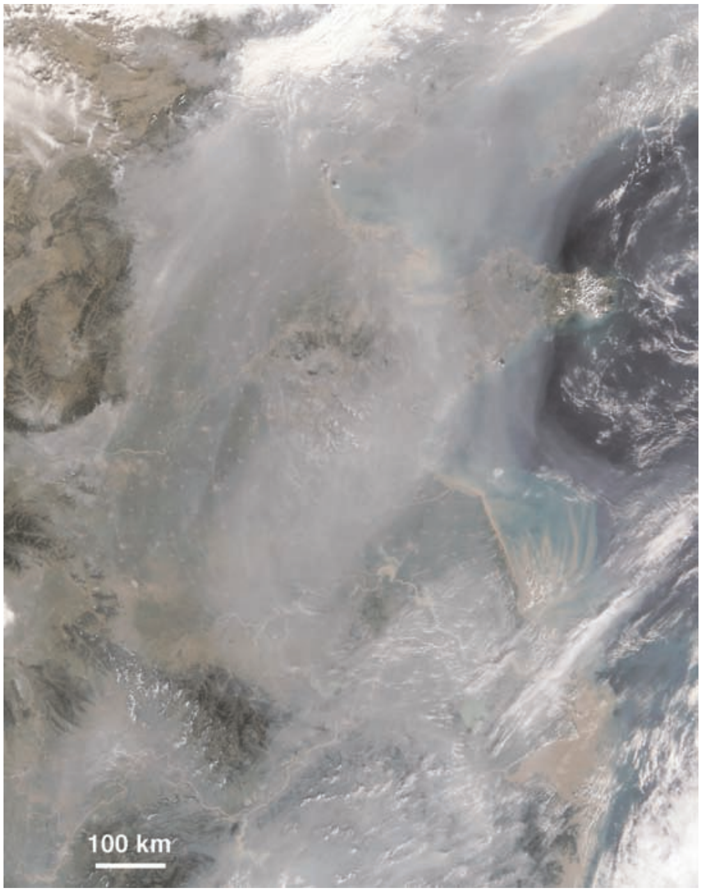

Figure 1. Smog over eastern China, September 10, 2005. Public domain image from NASA Earth Observatory: [http://earthobservatory.nasa.gov/Newsroom/NewImages/images.php3?img_id=17039], accessed February 20, 2008.

are also only apparently renewable (or limitless) at their current usage levels. For example, the sun delivers about 6000 times as much energy to the surface of the planet as current human demand requires. But if solar power were to supply all this demand, then large areas of the globe would have to be covered with solar panels, e.g. an area equivalent to about 2% of the Sahara Desert, or ~200 000 km^2, on each side of the planet (from data provided at [http://en.wikipedia.org/wiki/Photovoltaic_array] and [http://en.wikipedia.org/wiki/Photovoltaics#Grid_parity], accessed on February 20, 2008). This, in turn, would have major effects on local climate conditions due to absorption of solar heat. Significantly, however, this might have the short-term advantage of reducing atmospheric warming while at the same time reducing greenhouse gas emissions.

Even within the category of non-renewable resources, there is wide variation in the fate of these materials. The burning of fossil fuels, for example, is perhaps closest to a truly non-renewable usage, because once the fuel is burned it cannot be regenerated (except on timescales of tens or hundreds of millions of years). Usage of metals, however, includes the potential for recycling or reuse; indeed, some metals like copper, lead, and gold are recycled to high degrees today, such that the stock is depleted little by usage. In this sense, metals are potentially renewable, although at the expense of significant amounts of energy needed for their recovery, and some inevitable usage and processing loss. But the stock in the ground is not being regenerated on human timescales, and global economic growth continually demands more metals — a demand that recycling cannot meet unless new designs use materials more efficiently (i.e. reduced resource intensity, or dematerialization) and in ways that facilitate recycling.

LIFE vs. ENTROPY

Life, in thermodynamic terms, is a constant fight against entropy. Living organisms are not thermodynamically stable with respect to their environment, as shown by their general combustibility in air and the rapid decay of their structures upon death. While they are alive, however, they reverse the normal tendency for entropy to increase by expending energy:

$$\Delta G = \Delta H - T\Delta S$$

at fixed P, T (in Kelvin).

For a chemical reaction to proceed, the free energy change (ΔG) must be negative. If a reaction results in a decrease in entropy (ΔS negative but $-T\Delta S$ positive) then ΔH, the change in enthalpy or heat content, must be negative (i.e. energy is absorbed, and the reaction is endothermic; see Ernst 2002).

The required energy for these reactions is derived either directly (e.g. from sunlight by photosynthesis) or indirectly by ingestion of energy-rich nutrients, and is used to build and maintain the living organism, and to procreate its species. It is this directed fight against entropy that distinguishes living from dead objects, and humans have taken the fight to a whole new level.

Humans have evolved beyond the instinctual urges of survival and species dominance (i.e. to maintain or increase the order represented by the species) to consciously control their environment in order to develop and protect society. By current standards, the degree of societal development is largely measured by consumption rates (personal growth and comfort), accumulation of material possessions (asset growth), and accumulation of wealth (which can be converted into consumable or material possessions). These traits are manifested by a currently unbridled demand for food, water, materials, and energy, all of which must be extracted from the environment.

Energy is the key ingredient in societal development because it is required in the provision of all the goods noted above. In particular, energy is required to decrease the entropy of impure natural materials (e.g. ores) to produce pure products (e.g. metals). The limited availability of energy sources on the Earth's surface

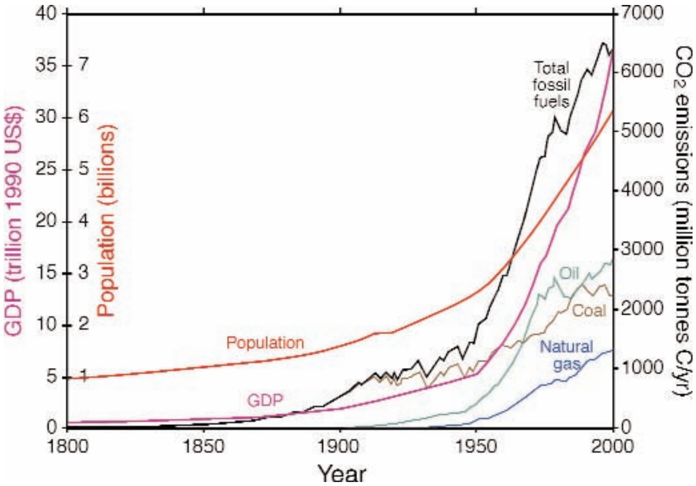

Figure 2. Comparison of the growth of world population, GDP, and CO_2 emissions from fossil fuels (as a proxy for fossil fuel usage). Sources of data: World population and GDP estimates (in 1990 US dollars converted at "Geary-Khamis" purchasing power parities) from Angus Maddison, *Historical Statistics for the World Economy: 1-2003 AD* [http://www.ggdc.net]; CO_2 emissions from Marland et al., *Global CO_2 Emissions from Fossil-Fuel Burning, Cement Manufacture, and Gas Flaring: 1751-2004* [http://cdiac.esd.ornl.gov/trends/emis/tre_glob.htm], accessed February 20, 2008.

Figure 3. Stirling Range National Park, southwestern Australia: a 65-km long tract of relatively undisturbed mountainous land surrounded in all directions by farmland. Public domain image from NASA Earth Observatory: [http://earthobservatory.nasa.gov/Newsroom/NewImages/images.php3?img_id=16950], accessed February 20, 2008.

(mostly wood) restricted the scale and rate of human societal development for most of its history, until the large-scale extraction of underground fossil fuels (initially coal) was used to power the Industrial Revolution in the later decades of the 18th century. Coal remains an important energy source today, but the higher calorific content and transportability of petroleum and natural gas made hydrocarbons the fuel of choice in the 20th century, and so far in the 21st century (Fig. 2).

A DISEQUILIBRIUM STATE?

Life has been altering the state of equilibrium of the Earth's environment since it first appeared. Probably the most far-reaching change was effected by cyano-bacteria that oxygenated the atmosphere and thereby enabled the evolution of aerobic organisms, while at the same time fundamentally changing surface processes such as weathering and sedimentation.

These changes were very slow, operating over timescales of hundreds of millions of years, and under conditions of almost steady-state dynamic equilibrium. In contrast, the scale and rate of change resulting from human industrialization and mechanization since the 1800s has been staggering, and represents a forced shift from surface equilibrium conditions. For example, almost 50% of the Earth's surface now shows visible effects of human activity, especially agriculture and urbanization (Fig. 3; Crutzen 2002) [see also Earth Observatory images of land-use change in the eastern United States from 1850 to 1920 at: http://earthobservatory.nasa.gov/ Newsroom/New Images/images. php3?img_id= 17920]; furthermore, the CO_2 content of the atmosphere has increased by ~36% from pre-Industrial Revolution levels (from ~275 to ~375 ppm; Intergovernmental Panel on Climate Change, 2007). As described above, these anthropogenic changes have been effected by the expenditure of enormous amounts of energy to physically extract and purify raw materials, to reverse selected chemical reactions to yield desired products such as metals and chemicals, in the mechanization of agriculture, and generally to power a technologically advanced civilization.

In particular, fossil fuel deposits built up over millions of years are being extracted and burned today at record rates (Fig. 2). For example, 5.4 billion tonnes of coal were produced globally in 2006 (World Coal Institute, 2007), and 30 billion barrels of petroleum and other liquid fuels were consumed in 2004 (Energy Information Administration, 2007). Burning fossil fuels at this rate is causing major perturbations in the composition of the Earth's atmosphere (increasing CO_2 and NO_X contents globally, as well as major regional emissions of acid rain-generating SO_2) and other environmental effects such as heavy metal pollution (especially of Pb and Hg). This represents a significant shift in the Earth's surface equilibrium state, which may have long-term effects on the environment (i.e. our habitat).

The extraction and processing of minerals is estimated to account for approximately 7% of annual world energy use, of which the smelting and refining of aluminium is one of the biggest consumers, requiring large amounts of electricity. In addition to these energy demands and corresponding impacts, mineral extraction exposes large volumes of reactive and toxic waste materials to the surface environment. These waste materials, commonly in the form of non-economic sulfide minerals such as pyrite, while stable in the relatively reducing environment beneath the Earth's surface, react quickly if allowed to contact atmospheric oxygen and water, to generate sulfuric acid:

$$2\,FeS_2 + 7.5\,O_2 + 7\,H_2O \rightarrow 2\,Fe(OH)_3 + 4\,H_2SO_4$$

This acid, in turn, accelerates the breakdown of other minerals, releasing

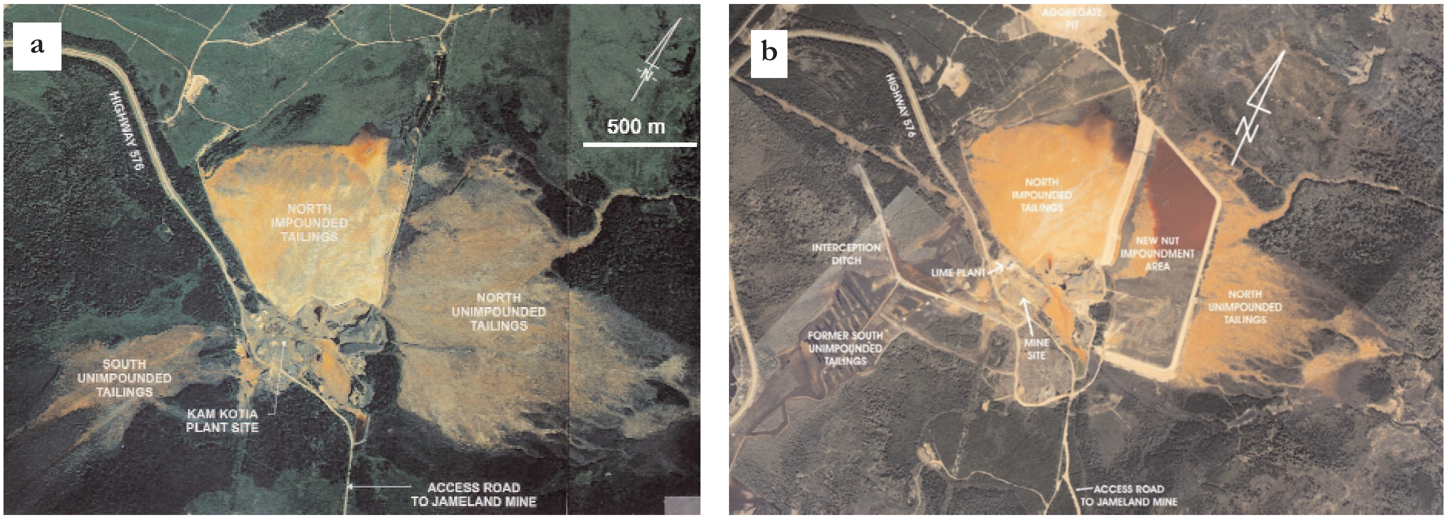

Figure 4. a) Aerial view (1989) of tailings spill from the Kam Kotia Mine site, near Timmins, northern Ontario; b) Cleanup operations under way in May 2003; rehabilitation is expected to cost the taxpayer of ~$50 million. Photographs are from the website of the Ontario Ministry of Northern Mines and Development: [http://www.mndm.gov.on.ca/mndm/mines/mg/abanmin/kamkotia_e.asp#top], accessed February 20, 2008; protected by Crown copyright (held by the Queen's Printers for Ontario), but may be reproduced for non-commercial purposes.

and mobilizing toxic trace metals such as Hg, As, and Pb. Modern tailings and waste-rock management practices aim to contain, slow down, or prevent entirely these reactions from occurring. However, where uncontrolled (as was the case in many older mines), these reactions can be self-sustaining for decades or even centuries, producing acid mine drainage (AMD) and heavy-metal contamination. Such problems characterize many abandoned mine sites worldwide, including an estimated 60 sites in northern Canada alone (Struzik 2003). One such site is the former Kam Kotia massive sulfide mine in northern Ontario, where unimpounded tailings have contaminated larges areas of land and water with AMD (Fig. 4).

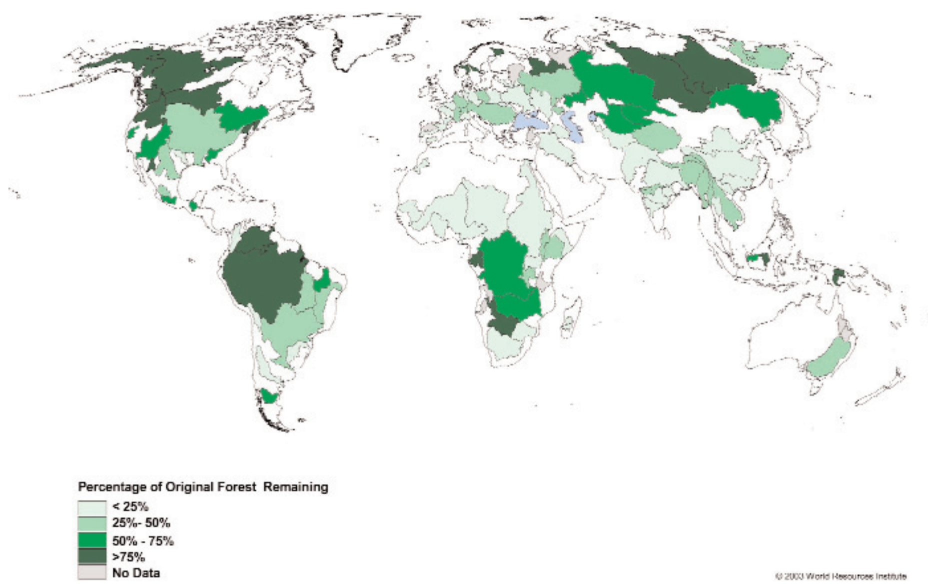

Figure 5. The extent of global forest loss by watershed, relative to forest cover 8000 years ago (International Union for Conservation of Nature et al. 2003). Forty-two catchment areas have ≤25% of their original forest cover. Reproduced with kind permission from the World Resources Institute.

Thus, by using large amounts of energy that was previously stored in stable underground deposits, humans have reversed a wide range of chemical reactions to produce goods and services (such as heating, lighting, and power) that are not in equilibrium with normal conditions on the surface of the planet. Some of these reaction products, such as spent nuclear fuels, will remain in a dangerously unstable state for millennia, whereas other products, such as chlorofluorocarbons, have had immediate and deleterious impacts on the atmosphere. Massive increases in greenhouse gas emissions (Fig. 2) over the last century appear to be having a somewhat slower but potentially even greater impact on climate, on timescales that could prove problematic even for the next generation. Humans have thus created an unstable environment for themselves, with the risk that this instability will be corrected involuntarily. That risk is particularly high if the increasing amounts of energy needed to maintain this disequilibrium state cannot be found.

GLOBAL RESOURCE INVENTORIES VS. DEMAND

The current state of human development is stuck on the need for personal growth and gain, projected as far as immediate family and extant generations, but rarely further. The horizons of political and industrial decision-making are even shorter, rarely extending beyond the next election or quarterly report. Concerns about consumption rates only arise when a shortage actually occurs, and little attention is paid to the state of the resource while it is still abundant. Thus, most of Europe was deforested for fuel and timber by the 18th century, when the shortage of this resource forced use of new alternatives — coal for fuel and steel for construction. The vast oak forests of Europe have not grown back (Fig. 5), but the environmental legacies of widespread coal-fired power generation and steel-making remain.

We face a similar situation with hydrocarbon resources today. Despite the oft-cited failure of the prediction by the Club of Rome that oil would run out by 1992 (Meadows et al. 1972), it most definitely will become too scarce and expensive to extract at some point, and at the time of writing oil prices are at record highs (mainly reflecting uncertainties in supply).

These high prices have also made the extraction of oil from Alberta's tar sands economic, although almost as much energy (currently in the form of cheap natural gas) must be expended in the extraction process as is contained in the product. This is particularly the case for in-situ steam-assisted gravity drainage extraction (SAGD), which is used to extract deeper deposits, where estimates range from 25–66% of the amount of energy produced as fuels must be expended in the extraction process. Moreover, relatively clean (in the sense of greenhouse gas generation) energy sources such as natural gas, and in current proposals, nuclear energy, are being used to produce relatively dirty petroleum fuels. Each conversion of fuel to do useful work involves a significant loss of energy, as dictated by the Second Law of Thermodynamics. Thus, a two step conversion of natural gas or uranium to generate energy, which is then used to produce oil to generate energy to power cars, is obviously much less efficient than using the natural gas or uranium as direct energy sources.

In the case of mineral resources, predictions of resource depletion are complicated by the possibilities of substitution and recycling. The best indicator of resource scarcity is price, although short-term price fluctuations are more correctly an indicator of supply and demand than actual resource inventory (i.e. prices can be dramatically affected by political, economic, or natural events that physically affect short-term supply and demand; Tilton 2006). Whereas there is little short-term option to switch fossil fuel types (e.g. between oil or gas or coal), minerals show greater substitutability in response to price changes. A good example is in the auto industry, where use of platinum or palladium in catalytic converters has historically alternated depending on price. Similarly, the use of copper in plumbing and telecommunications has been replaced by plastics and fibre optic cables in many markets, and both gold and aluminum are used in electronic and electricity transmission applications. Thus, if copper resources were to become scarce and its price were high enough, then several other metals or materials could replace it.

Most metals and minerals, including copper, lead, aluminium, all the precious metals, and many aggregates, are today recycled to varying degrees. The degree of recycling of a commodity depends both on its inherent value and also the ease with which it may be recycled. Thus, copper and lead are easily recovered in their pure states from cables and lead-acid batteries, but alloyed metals such as steel, brass, and bronze are less easy to recycle because they are mixtures of elements such as chromium, nickel, zinc, and tin, in addition to iron and copper. Unless scrap is carefully screened by alloy type, the amount of energy needed to separate these elements to produce a usable product becomes prohibitive, to the point that it is cheaper to use newly mined minerals (see Ayres et al. 2003, for a detailed analysis of the economics and practicalities of recycling in the copper industry).

As implied in the previous discussion, the price and availability of metals is an economic construct. In theory, there are indeed virtually unlimited amounts of most metals in the Earth's crust. Their concentrations in average crustal rocks are, however, too low to be mined economically at present. Thus, mineral exploration seeks to find greater concentrations of the element(s) of interest in order to reduce the cost (primarily energy costs) of extraction. It has been argued by some that the declining number of discoveries of "giant" ore deposits and the falling grades of mined ore together indicate that large, higher grade orebodies are becoming scarce, and that the industry is being forced to mine lower grade orebodies (Lambert 2001). In reality, however, this is an oversimplification of a complex interrelationship between geology, mineral processing technology, mineral economics, and geopolitics. New high-grade orebodies continue to be found, but commonly in politically risky or remote parts of the world that have not yet been explored extensively. On the other hand, new mining, mineral processing, and metallurgical technologies (such as open-pit bulk mining, energy-efficient fine-grinding, underground mineral processing, sulfide flotation, heap-leach extraction, bio-oxidation, solvent extraction–electrowinning, and flash smelting) have enabled lower grade or complex ores to be processed economically (Hoal et al. 2006). The result is that when mine reserves are calculated, the higher grade ores are diluted with larger tonnages of lower grade material until an optimal balance of mill throughput and metal production is achieved. In other words, although a good profit could potentially be made by mining just a small volume of high-grade ore, a larger profit and longer mine life can be achieved by mining a much larger orebody of lower average grade.

Skinner (1976; see also Ernst 2002; Tilton 2003, 2006) has argued that the distribution of elements in nature may not be smooth, and that ore-forming processes may create a bimodal distribution of element concentrations: low background levels, with localized high concentrations in ore deposits. The implication of this view is that there may be a finite supply of ore deposits, which once found and mined, will leave only background concentrations that will be prohibitively expensive to extract, the expense being the cost of the energy required to separate the element or mineral of interest. However, this view ignores the economic definition of what is "ore". In very few mines is there a sharp concentration cut-off between "ore" and "waste"; instead, the boundaries of ore zones are delimited by what can be economically extracted given the metal prices and operating costs of the day. This means that many orebodies still contain a lot of metal after mine closure, albeit at lower grades. It also means that mines commonly operate long past their original design life, or are re-opened after closure, because either new ore zones are found, or new technologies are developed that enable mining of lower grade ores.

Calculations of the expected abundance of metals in ore deposits in the top 3 to 4 km of the Earth's crust (realistic maximum mining depths) also suggest that large amounts of metal remain to be discovered. For example, Frimmel (2008) estimated that only 7 x 10^{-5} % of available gold in the Earth's crust has been mined or identified in resources to date, and Kesler and Wilkinson (2008) calculated that the likely amount of Cu contained in upper crustal deposits would meet current demands for 5500 years.

Thus, it seems unlikely that supplies of minerals will ever physically run out. Instead, they may become sufficiently scarce that the cost of extraction, and therefore the price, will become greater than that of a substitute (Tilton 2003). However, there is little sign of this happening yet: the inflation-corrected price of most metals has in fact fallen, and resource inventories and production have risen over the last century (Tilton 2003; Richards 2005). Furthermore, mineral resource depletion on its own is unlikely to be a sudden event, because most commodities are sourced globally from multiple deposits and suppliers; thus, new extraction technologies or substitution strategies can be developed in response to slowly rising prices with minimal economic impact. In contrast, a major energy price shock is much more likely to occur because of the limited options for fuel supply and substitution. Such an energy shock would have much more catastrophic global economic consequences than the slow depletion of mineral resources.

SUSTAINABLE DEVELOPMENT AND HUMAN EVOLUTION

So what does sustainable development mean in the longer term sense implied by Porritt (2002) and from the perspective of human evolution? Assuming that humans will not in the foreseeable future populate other planets and assuming that we do not want to see a Malthusian-type collapse of our civilization (Malthus 1798), sustainable development means that we must devise ways of living within the capacity of our planet to support us. Supply and availability of minerals is probably, in fact, one of the least of our concerns. Much greater challenges relate to energy supply and availability of fresh water. At current usage rates (which are relentlessly growing), fossil fuels (apart from coal) will be exhausted as a cheap source of energy within the next few decades, even if their impact on climate is ignored. Fresh water, on the other hand, is already in dangerously low supply in many parts of the world, and droughts are predicted to increase with global warming (MacDonald et al. 2008). Conflicts over water supply, such as those occurring today in Darfur, are likely to become more frequent (Sachs 2008).

At the root of all of the above problems is global human over-population and population growth. This is not a popular topic, and in fact if one were to believe most western politicians, we should be encouraging population *growth*, not its decline. This view is fuelled by short-term worries over ageing populations in many developed countries (which is a valid concern but hardly insoluble) and the capitalist fixation on growth (which is not necessarily desirable in the long term; Ayres 1998). However, the greater issue of potential societal collapse should surely trump short-term concerns about unfunded pension liabilities and GDP, at least at some level of discussion in the decision-making process.

Other examples of short-term crises that have occupied the public's mind to the exclusion of potentially far more serious longer-term issues include globalization, climate change, terrorism, religious conflicts, and the addiction to oil. All of these are serious issues that need to be addressed, but they should not obscure a longer term view of where human society is heading, or draw attention away from more fundamental issues that could cause societal collapse (e.g. Diamond 2005). In the case of climate change, the Kyoto Protocol has been pursued with inordinate vigour and its goals (if met) will have been attained at great cost. However, even the strongest proponents of the protocol agree that it will only minimally slow, and certainly not reverse, climate change.

Some thinkers such as Bjørn Lomborg have argued that knee-jerk reactions to apparent crises such as global warming are commonly expensive and inappropriate, and better solutions to more serious longer term problems can be engineered for much less cost by careful planning and visionary thinking (e.g. the Copenhagen Consensus: Lomborg 2008). However, except perhaps in some parts of academia, modern culture has not progressed beyond ancient traditions, or indeed our pre-human ancestors, in not rewarding or valuing the long-term view. Even our religions focus on reward for the individual and immediate advancement of the tribe, but not of humanity as a whole.

Thus, signing up to the Kyoto Protocol (with the bill to be paid by future taxpayers) is rewarded politically in most countries, but committing a small fraction of that sum to research into truly sustainable forms of energy production, for example, gets little support. Meanwhile, the fossil fuel industries enjoy massive worldwide government support and subsidies. For example, many have argued that the costs of the recent Gulf Wars measured in hundreds of billions of dollars, [http://www.nationalpriorities.org/costofwar_home] should be booked against the cost of securing oil supplies to the west.

Given that, in many cases, "the right thing to do" is quite apparent but is not rewarded by our economic or cultural structures, nor reinforced by our own nature, is it likely that modern humans will be able to resolve the dilemma of safeguarding the longer term interests of our species, while living comfortably and equitably today? Most species, when cornered in this way, either evolve or die — a fairly stark choice. Humans are of course evolving physically, generally growing taller and fatter, at least in the developed world. But it is not the physique of humans that is the problem, nor the solution. Rather, it is the human mind that needs to evolve to catch up with the incredible pace of human technological progress. We now have the technology to destroy ourselves many times over, cure most diseases, and send people to the moon or the bottom of the ocean. But we do not seem to be able to agree collectively (i.e. globally) on very much at all (witness the stalemate in the Doha Development Round of trade negotiations, and the watering down of the Kyoto Protocol). Likely, the evolutionary change that will enable humans to survive in the medium to long term on this small planet will be the ability to think and act for the collective human benefit on these longer timescales, instead of for the short-term benefit of ourselves and our immediate offspring (Rees 2008). In 1892, Friedrich Nietzsche foresaw this need in his depiction of the "overman" (Übermensch) in *Thus Spoke Zarathustra*, although he was a century ahead of his time, and his ideas were subverted to terrible effect by the Nazis. His portrayal of the alternative was as an evolutionary dead-end, the "last man":

> *"The Earth has become small, and on it hops the last man, who makes everything small. His race is as ineradicable as the flea-beetle; the last man lives longest."* (Nietzsche 1978, p. 17)

Rees (2008) views the path to collective sustainability as being one of willpower, and it may be that humans are the first species to live on this planet that can plan its own constructive evolution (instead of being subject to forced change by the effects of random cosmic rays or external ecological factors). Rees makes no prediction as to the likelihood of this outcome in his essay, but I would venture to be optimistic. Karr (2008), writing in the same book as Rees (2008), suggests that to "protect society from itself":

> *"Thoughtful people must not cede all power to politicians and business interests; we must make our voices heard across the full range of professional, social, and civic circles."* (Rees 2008, p. 95)

As geoscientists, I believe we are well placed, and have an obligation, to enter this debate, if only because our science appreciates the depths of geological time, and the fleeting transience of species in Earth's long history. It is unlikely that climate change will destroy our planet, but unchecked and inequitable resource consumption will quite possibly destroy our civilization.

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Note added in Proof:

Readers' attention is drawn to a recent article by Chaisson (2008), which considers and quantifies the effects of waste heat derived from human technological and energy-generating activities, as an unavoidable consequence of the Second Law of Thermodynamics. Chaisson (2008) argues that this is likely the most serious threat to the stability of the environment, and would continue to heat the world even if all greenhouse gas emissions were stopped immediately. It is an inevitable consequence of technological growth and development. From this perspective, the only energy source that would not add heat to the environment by its usage is terrestrially-captured solar energy; in fact, its usage could be almost heat-neutral, because energy that would otherwise be dissipated in the environment on a daily basis is being captured and utilized.

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