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Article

The Human Ecology of Overshoot: Why a Major ‘Population Correction’ Is Inevitable

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Abstract: *Homo sapiens* has evolved to reproduce exponentially, expand geographically, and consume all available resources. For most of humanity’s evolutionary history, such expansionist tendencies have been countered by negative feedback. However, the scientific revolution and the use of fossil fuels reduced many forms of negative feedback, enabling us to realize our full potential for exponential growth. This natural capacity is being reinforced by growth-oriented neoliberal economics—nurture complements nature. Problem: the human enterprise is a ‘dissipative structure’ and sub-system of the ecosphere—it can grow and maintain itself only by consuming and dissipating available energy and resources extracted from its host system, the ecosphere, and discharging waste back into its host. The population increase from one to eight billion, and >100-fold expansion of real GWP in just two centuries on a finite planet, has thus propelled modern techno-industrial society into a state of advanced overshoot. We are consuming and polluting the biophysical basis of our own existence. Climate change is the best-known symptom of overshoot, but mainstream ‘solutions’ will actually accelerate climate disruption and worsen overshoot. Humanity is exhibiting the characteristic dynamics of a one-off population boom–bust cycle. The global economy will inevitably contract and humanity will suffer a major population ‘correction’ in this century.

Keywords: overshoot; exceptionalism; human nature; cognitive obsolescence; exponential growth; ‘K’ strategist; over population; over consumption; climate change; energy transition; dissipative structure; civilizational collapse; population correction



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1. Introduction and Purpose

This paper examines the human population conundrum through the lens of human evolutionary ecology and the role of available energy. My starting premises are as follows: (1) Modern techno-industrial (MTI) society is in a state of advanced ecological overshoot (for an excellent introduction to overshoot see William Catton’s classic, *Overshoot* [1]). Overshoot means that even at current global average (inadequate) material standards, the human population is consuming even replenishable and self-producing resources faster than ecosystems can regenerate and is producing entropic waste in excess of the ecosphere’s assimilative capacity [2,3]. In short, humanity has already exceeded the long-term human carrying capacity of the earth. (2) The fossil-fuelled eight-fold increase in human numbers and >100-fold expansion of real gross world product in the past two centuries are anomalies; they also constitute the most globally-significant ecological phenomena in 250,000 years of human evolutionary history, with major implications for life on Earth. (3) *H. sapiens* is an evolving species, a product of natural selection and still subject to the same natural laws and forces affecting the evolution of all living organisms [4,5]. (4) Efforts to address the human demographic anomaly and resulting eco-crisis without attempting to override innate human behaviours that have become maladaptive are woefully incomplete and doomed to fail.

Within this framing, the overall objective of the paper is to make the case that, on its present trajectory and regardless of the much-lauded demographic and so-called renewable

energy transitions, the sheer number of humans and scale of economic activity are undermining the functional integrity of the ecosphere and compromising essential life-support functions. Unaddressed, these trends may well precipitate both global economic contraction and a significant human population ‘correction’—i.e., civilizational collapse—later in this century.

2. The Nature and Nurture of Overshoot

Both nature and nurture contribute to the overshoot crisis, but the natural component is mostly ignored. Indeed, most denizens of MTI society do not think of themselves products of evolution, i.e., of Darwinian natural selection. Many resent even being reminded that they are animals.

Ironically, part of the reason for such denial resides in humanity’s extraordinary evolutionary success—we are the dominant, and certainly the most numerous, large mammal species on Earth. As much of this success is attributable to the abundance of resources made available by improving technology, cultural evolution receives all the credit. However, basic biology underpins all human cultures—even the capacity for socio-cultural organization is itself an evolved trait.

Of particular relevance in the present context are three innate abilities/predispositions that humans share with all other species. Unless constrained by negative feedback, populations of *H. sapiens* (1) are capable of exponential (geometric) growth, (2) tend to consume all available resources (a highly adaptive trait in the absence of refrigeration or other preservation techniques, or in the face of intense competition from neighbouring tribes), and (3) will expand to occupy all accessible suitable habitats. Significantly, in the case of humans, both the ‘availability’ (of resources) and ‘suitability’ (of habitat) are constantly being upwardly refined by technology, thus amplifying the underlying genetic predispositions.

We will return to population dynamics in a later section. Consider first industrial humanity’s characteristically insatiable demand for resources and habitat. Abetted by improving exploitation technologies, *H. sapiens* is depleting the seas and forests, has otherwise diminished wild nature, has destroyed a third of Earth’s arable soil and landscapes, has mined out the richest deposits of many mineral and metal ores and, in just a couple of centuries, has run through the high-quality half of the massive stocks of fossil energy that took tens of millions of years to accumulate. Society’s dependence on fossil fuels is one reason why the MTI mainstream sees an ice-free Arctic Ocean not so much as a climate catastrophe, but as the opening up of new trade routes and exposing the Arctic basin to oil and gas development. Meanwhile, having depleted the richest sources of dry-land mineral resources, some industries/countries are gearing up to mine the sea-floor—we will scour the bottom of our Earthly barrel! [6]. Looking ahead, still, others have set their sights on the presumed mineral wealth of asteroids or the moon as the next resource troves to be served up for exploitation [7].

This last point also hints at the third crucial trait noted above, humanity’s spatial expansionism. Can you think of any ecologically comparable species with a geographic range even remotely as large as that of *H. sapiens*? Hint: there is none—driven by our natural expansionist imperative, humans have colonized the entire planet—there is no significant patch of human-habitable landscape on Earth that we have not long since claimed as our own. We even occupy certain ‘habitats’ that are fundamentally hostile to human existence (think ‘Antarctic field stations’). Meanwhile, various entrepreneurs and humanist dreamers would have us colonize the Moon or Mars, not only for their resource potential, but to insure against the extinction of *H. sapiens* should Earthly life-support systems fail under the weight of human demands.

One might expect that an intelligent social species would devise cultural overrides to rein in potentially dangerous expansionist tendencies on a finite planet. Rather remarkably, the opposite is the case. One of the most important roots of overshoot is MTI society’s belief in human exceptionalism, the idea that *H. sapiens* is fundamentally different from other species. Exceptionalists posit that human individual and social behaviours

are culturally rather than genetically determined; that human ingenuity can overcome resource scarcities; that we are not otherwise bound by the laws and limits of nature. The corresponding economic paradigm, neoliberal economics—which currently underpins global ‘development’—implicitly assumes that the economy and the ‘environment’ are separate systems, so that the former, propelled by continuous technological advances, can grow indefinitely, unconstrained by the latter. Hubristic nurture unabashedly reinforces expansionist nature.

The evidence is compelling that human exceptionalism is a deeply-flawed construct—a grand cultural illusion—that has led MTI societies into a potentially fatal ecological trap. While culture contributes unique dimensions to humanity’s evolutionary trajectory, this does not exempt humans from the same fundamental principles governing the evolution of non-human lifeforms. The conflict between mass delusion and biophysical reality is increasingly evident in the destabilization of the ecosphere induced by the excessive scale of the human enterprise. No one should be surprised—as ecological economist, Herman Daly consistently argued, far from floating in splendid isolation, “the human economy is a fully-contained wholly-dependent growing subsystem of the non-growing ecosphere” [8,9].

Consider the implication of Daly’s insight for biodiversity loss, one of the most urgent symptoms of overshoot. *H. sapiens* is just one of an estimated 8.7 million species of animals and plants and countless millions additional species of bacteria, fungi, and other microbes. Most of these life-forms are dependent on a tiny fraction of solar energy ‘fixed’ as biomass through photosynthesis by green plants. Plants require up to half of this ‘gross primary production’ for their own growth and reproduction, so only the remainder—so called ‘net primary production’—is available for other life-forms. This residual supports all animal life, including humans, which means that we are competing with millions of other species for a share of a continuous, but limited flux of biomass through the ecosphere.

Humans, of course, have a technological ‘leg-up’ in the competition. Our high intelligence, technology-assisted harvesting techniques and fossil-fuelled ability to transform entire landscapes to suit human needs, means that, for centuries, humans have been increasing their appropriations from the annual global flow of biomass energy [10]. Fowler and Hobbs even ask whether, in terms of common eco-variables, contemporary *H. sapiens* is still ‘ecologically normal’ [11]. Their data show that in terms of energy use (and therefore carbon-dioxide emissions), biomass consumption and various other ecologically significant indicators, human demands on supportive ecosystems dwarf those of similar species by orders of magnitude. For example, human consumption of biomass exceeds the upper 95% confidence limits for biomass ingestion by 95 other nonhuman mammal species by 100-fold; as previously noted, humanity’s geographic range is unequalled, exceeding the upper 95% confidence limit for the ranges of 523 other mammal species by a factor of ten. Bottom line: Like other living organisms, *H. sapiens* have evolved biologically to self-maximize. However, combined with our unique cultural prowess, human “...abilities for growth vastly outstrip those of all other species, as is demonstrated by our domination of the biosphere. ...” [12].

The consequences for non-human animal species are catastrophic, for what should be obvious reasons. Not only do we typically overexploit targeted ‘resource’ species, but any biomass the human tribe takes for its own purposes is irreversibly unavailable to competing organisms. Humanity’s foraging superiority means the ‘competitive displacement’ of other species from their food sources and habitats. The ‘other species’ consequently decline or die off. While *H. sapiens* comprises only 0.01% of the total Earthly biomass, the expansion of the human enterprise has eliminated 83% of wild animal and 50% of natural plant biomass. From a fraction of 1% 10,000 years ago, humanity now constitutes 32%, and our domestic livestock another 64%, of the planet’s much expanded mammalian biomass; all wild species combined account for only 4% [13]. Similarly, domestic poultry now comprises 70% of the earth’s remaining bird biomass [13,14] and commercial fishing depletes the oceans at the expense of rapidly declining fish-dependent marine mammals and birds. Seabirds are the most threatened bird group, with a 70% community-level population decline between

1950 and 2010 [15]. The remaining populations of monitored vertebrate species have also declined by ~70% in the past half-century [16].

These and related data suggest that our species has become, directly or indirectly, the dominant macro-consumer in all major terrestrial and accessible marine ecosystems on the planet. Indeed, *H. sapiens* may well be the most voraciously successful carnivorous and herbivorous vertebrate ever to walk the Earth—but at the expense of thousands of other species. The growth of the human enterprise (population and economy) on a finite planet is the greatest factor contributing to plunging biodiversity [17]. Reduced human populations almost everywhere are necessary to preserve remaining patches of non-human life on Earth [18].

Of course, biodiversity loss is only one major symptom of overshoot. Overshoot is a meta-problem, the cause of climate change (including desertification, faltering ocean circulation, etc.), land/soil degradation, tropical deforestation, ocean acidification, fisheries collapses, sinking water tables, incipient food shortages, plastic and other chemical contamination of food chains, falling sperm counts, increasing cancer rates, pandemics, the pollution of everything, etc. Virtually all so-called environmental problems are co-symptoms of overshoot. We humans are depleting and contaminating the biophysical basis of our own existence.

In the process, the human enterprise has also become the most significant of contemporary geological forces—people move up to 24 times as much material around as all natural geological processes combined [19,20]. Little wonder that the sheer weight of human-made stuff now exceeds the living biomass on Earth (~1.1 terratonnes) [21]. Welcome to the Anthropocene [22,23].

There is more than a touch of irony lurking behind these biophysical realities. Economists and techno-optimists hallucinate that the economy is ‘dematerializing’ or further ‘decoupling’ from the material world on such simplistic grounds that the ratio of carbon emissions or resource use per unit GDP is declining [24]. The above data illuminate the contrary fact that, in terms of what really matters to nature—the expanding human ecological niche—humans are actually becoming an ever greater and more destructive integral component of the ecosphere [25]. Indeed, the human enterprise is effectively subsuming the ecosphere.

Nevertheless, the bizarrely nonsensical myth of decoupling persists. Politicians lean on technology—efficiency and ‘dematerialization’—to argue that there is no inherent conflict between the continued growth of the economy and ‘the environment.’ They speak from naïveté or ignorance, but this assertion encourages the all-too-willing public to share in one of the most toxic of humanity’s panoply of illusions.

Why Is Nobody Listening?

In light of the cascading hard evidence, it seems fair to ask why the mainstream media do not report on, and most ordinary people have never heard of, overshoot. Much of the reason may be simple denial, but part of the problem may well reside in cognitive incompetence. *H. sapiens* evolved in simpler, more slowly-changing times that posed relatively limited challenges to the evolving central nervous system. We operate with what are still essentially Palaeolithic brains: modern humans are painfully short-sighted [26], tend to think in terms of immediate cause–effect relationships and respond to problems in simplistic, reductionist ways (think ‘dematerialization’). This cognitive mode was adequate in pre-agricultural times. However, in recent centuries, cultural evolution (e.g., the emergence of multi-layered cultures, global institutions, and near-magical technologies) has outpaced bio-evolution [27,28]. Our brains are arguably ill-adapted to the pace of change and compounding complexities of the human-made Anthropocene—we have rendered ourselves cognitively obsolete [29].

Perhaps the most obvious example is the global fixation on climate change as *the* existential threat facing civilization. The media may be temporarily side-tracked by the recent pandemic, regional famines, the growing refugee crisis, or the Russo–Ukraine war, but the focus is still on one isolated issue at a time. Rarely do the media, even

serious analysts, and certainly not most politicians, connect the dots to see these issues as springing from a common root in overshoot. Even the term poly-crisis (many parallel related problems) does not quite cut it. MTI peoples simply do not ‘get’ complexity; nor do they comprehend the lags, thresholds, and unpredictably discontinuous behaviours of overlapping complex systems under stress from overshoot [30]. This is crucially important if only because, while no major symptom of overshoot can be adequately addressed in isolation from the others, addressing overshoot directly would reduce all important symptoms simultaneously.

3. The Population Connection

“The human mind serves evolutionary success, not truth. To think otherwise is to resurrect the pre-Darwinian error that humans are different from all other animals” (John Gray, [31]).

Which brings us back to the population conundrum. In the simplest terms, overshoot results from too many people consuming and polluting too much. The immediate physical cause is excess economic throughput (i.e., resource consumption and waste production), but throughput is itself driven by both rising incomes and population growth. Most people tend to spend/consume to the limit imposed by their discretionary incomes (and, since the introduction of easy credit, often well beyond). High-income countries and populations are therefore responsible for three quarters of excess material consumption and pollution to date [32]. Even in 2021, “the top 10% of emitters were responsible for almost half of global energy-related CO₂ emissions. . . compared with a mere 0.2% for the bottom 10%” [33]. For the past several decades, however, incremental increases in humanity’s consumption-based ecological footprint (EF) and carbon emissions have been driven more by population growth than increased incomes/consumption in all income quartiles. Indeed, population growth accounted for ~80% of the increase in the total human EF above what would have accrued had populations remained constant even as incomes increased [34,35].

In this light, it is worth noting that, in 2023, about four billion people (half the human family) reside in lower-middle income and low-income countries, those countries with the highest population growth rates and whose people have yet to satisfy their material needs. The combination of population growth, massive latent demand, and rising GDP/capita—the latter fully justified—represents a huge potential increase in future global consumption/pollution, poses a double challenge to ecospheric integrity on a planet already in overshoot, and—rather belatedly—underscores the need for greater equity in access to resources for the world’s peoples.

It should also be obvious from these data and trends that any global approach to harmonizing the human enterprise with the ecosphere must include population planning. Nevertheless, until recently, the population question was out of bounds even in academia, largely on religious/cultural/humanist grounds or often spurious charges that analysts were implicitly racist [36,37]. As the ballooning costs of extreme weather, biodiversity loss, land/soil degradation, wildfires, regional famines, energy shortages, pollution, etc., affect more and more people, the obvious benefits of smaller human numbers [38] are finally dissolving the population taboo.

While it is becoming increasingly important that policy analysts and politicians fully understand what ‘population’ is all about, they will not receive a complete picture from most mainstream demographers. Oddly, despite their focus on population dynamics, demographers make little reference to key elements of population biology or environmental influences. Most human population projections are based on purely demographic factors—base population, age/sex distribution, age specific fertility, and mortality rates and migration (where applicable), i.e., they are conducted in a contextual vacuum. In addition, faulty inputs may skew the outcome. Population analyst, Jane O’Sullivan, argues that the flawed assumptions of the UN’s population model [39,40] and even that of the Earth4All consortium [41], place their projections “firmly in the realm of fairy tale” [42,43]. The UN expects the human population to peak at ~10.4 billion towards the end of the

century. Earth4All's 'Too Little Too Late' peak projection is for ~8.7 billion in the early 2050s; its 'Giant Leap' estimate tops out at ~8.4 billion in the early 2040s. Even with reasonable demographic assumptions, model results will be valid only if all exogenous factors crucial to population health and security can be maintained through the projection period. This assumption is simplistically unrealistic—the population is in a state of advanced overshoot dangerously eroding human carrying capacity. Climate scientists, ecologists, environmentalists, and even some demographers [44] are now sounding the alarm over mounting population pressures, even arguing we would all be better off if there were fewer of us [38].

The Evolutionary Roots of 'Population-as-Problem'

Every concerned citizen should understand the basics of human population dynamics. First, as noted at the outset, human populations, like those of all other species, are capable of exponential (aka 'geometric') growth under favourable environmental conditions. A population growing exponentially at a fixed rate will have a constant doubling time. For example, the human population reached its peak growth rate of 2.2% per annum in the early 1960s when the global population was about 3.2 billion; had this rate been sustained, the population would have continued doubling every 32 years. As matters stand, the average fertility rate has declined so the population has increased 'only' 2.5 times in 60 years.

Exponential growth is a form of positive feedback where each increment to the population adds to the reproductive base, just as annual interest adds to the capital in a bank account. However, under natural conditions, most species (including humans) rarely realize their full reproductive potential. Positive feedback growth is countered by various forms of negative feedback—disease, food shortages, hostile competitors, etc.—so that natural populations typically fluctuate around a long-term mean. Numbers rise when conditions are favourable and fall when conditions change for the worse, often because of the bloated population itself—disease is easily spread, and starvation may be caused by excessive population densities.

Evolutionary biologists recognize that different species have evolved different reproductive strategies. Humans are archetypal 'K'-strategists: 'K'-strategic species are typically large, long-lived organisms, with relatively low reproductive rates, long-gestation periods, intensive parental care, and low infant mortality rates. At the other end of the spectrum are 'r' strategists, typically smaller, short-lived organisms with short life-cycles, very high fecundity ('r'), little parental investment, and high progeny mortality rates. Species continuity depends on the survival of a tiny percentage of very large numbers of offspring. K-strategists are most frequently adapted to relatively stable habitats where, because of high survival rates, they tend to press up against the local carrying capacity ('K') [45]. Carrying capacity is the average maximum sustainable population for a particular habitat; thus 'K' represents the fluctuating equilibrium established between the species' geometric growth potential and various negative feedbacks (e.g., food/water shortages and spatial limitations) that kick in when conditions deteriorate or excess numbers stress the habitat. These dynamics were the basis for Malthus' concern, that population growth potential would always outstrip food supply.

Why is this significant again today? As noted at the outset, anatomically, modern humans have been around about 250,000 years. For most of this period, the population growth curve was essentially flat. There was a barely detectable global increase as *H. sapiens* spread from Africa over the rest of the planet over the past 50 millennia, and a modest uptick with the adoption of agriculture 10 millennia ago, but for the most part, widely-dispersed human populations have historically fluctuated close to their local carrying capacities. Suppressed by negative feedback, it took 99.9% of human history for the world population to reach one billion in the early 1800s.

With the scientific and industrial revolutions, everything changed. In particular, improving public health greatly lowered mortality rates and the increased use of fossil-fuelled technologies both steadily increased the availability of food [46] and provided the means of access to all the other resources needed to grow the human enterprise. In

just 200 years ($1/1250$ th the time it took to reach the first billion), the human population ballooned to seven billion by 2011 and reached eight billion only 11 years later, in November 2022. Meanwhile, human material demands on the ecosphere increased by more than two orders of magnitude with a greater than 100-fold increase in real gross world product (GWP) [47]. Ironically, only ~eight out of 10,000 generations of humans have lived this briefest of notable periods in human evolutionary history, yet today's MTI society takes this utterly anomalous growth spurt to be the norm—and is doing everything conceivable to maintain it (Figure 1).

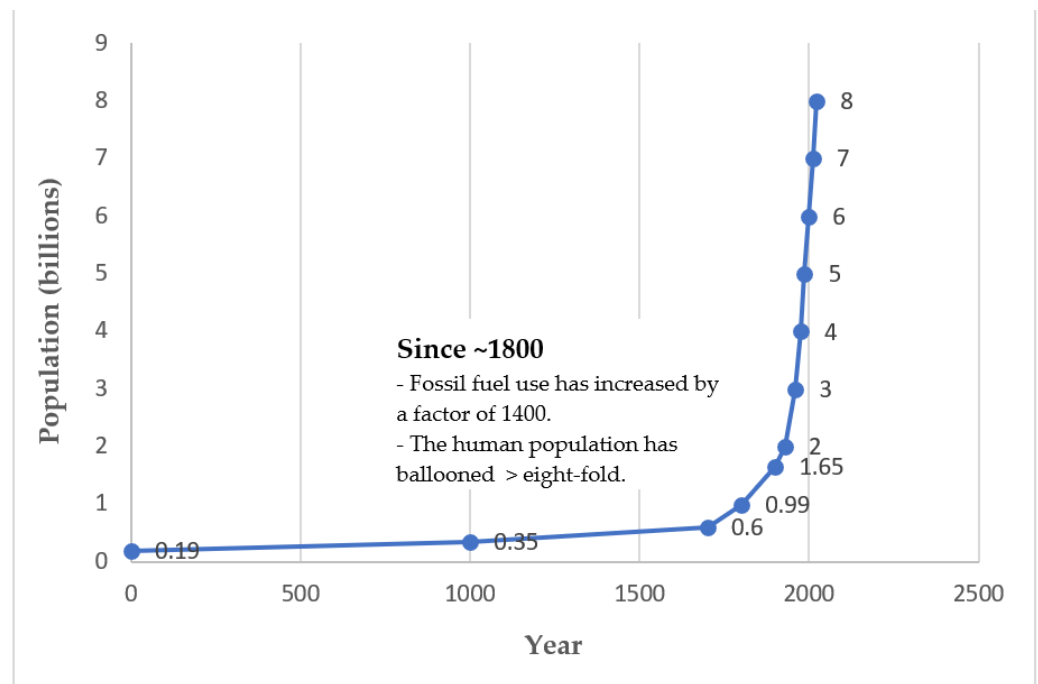


Figure 1. The anomalous fossil-fuelled human population boom.

4. On Energy Gradients: *H. sapiens* as a ‘Dissipative Structure’

“...we use 30 percent of all the energy, in the United States. That isn’t bad; that is good. That means that we are the richest, strongest people in the world and that we have the highest standard of living in the world. That is why we need so much energy, and may it always be that way” (US President Richard Nixon, November 1973 [48]).

The history of human population growth underscores a key factor to understanding the eco-crisis, one that is generally ignored by economists and demographers—the population bomb was assembled during the industrial revolution and exploded in the 19th century with the expanding use of fossilized organic matter that took hundreds of millions of years to accumulate. The wealth creation and technologies enabled by fossil fuels (FF)—including fertilizers and pesticides—reduced or eliminated various historically important forms of negative feedback, freeing the world’s human population to grow exponentially for the very first time. The fossil-powered explosion of the human enterprise triggered the most significant period of global ecological degradation in 250,000 years of human evolutionary history.

Understanding the role of energy also helps illuminate humanity’s future prospects. Following on mathematician Ludwig Boltzmann’s observation that the Darwinian struggle for existence is essentially a competition for available useful energy, mathematical ecologist, Alfred Lotka, proposed in the 1920s that successful systems (individuals, species, and ecosystems) were those that maximized their appropriations and effective use of available energy (exergy) from their environments [49]. Somewhat later, ecologist Howard Odum refined and formalized the basic concept as the ‘maximum power principle’: in

essence, natural selection favours systems that evolve (self-organize) in ways that maximize their energy intake and power output in the service of self-maintenance, growth and reproduction [50,51]. Systems that markedly fail to maximize their useful power output would be selected out.

H. sapiens are arguably the archetypal demonstration of maximum power. While other animal species are dependent on bodily (endosomatic) energy obtained from ingested biomass, humans are uniquely capable of using supplemental out-of-body (exosomatic) energy toward systems growth and reproduction. The history of civilization traces a sequence of external energy sources beginning with fire, flowing water, and wind, evolving through FF, hydro-electricity, and other so-called modern renewables, to nuclear power. Comparing societies from hunter–gatherers through farmers to MTI culture shows a pattern of exosomatic energy use, increasing from 20 Gjoulles/person per year through 60 Gjoulles/person per year to 300 Gjoulles/person per year, respectively [52]. The richest, most powerful and thus successful (by contemporary criteria) cultures, societies, and nations have always been those that maximize their appropriations and effective use of available energy. As noted earlier, the explosive increase of GWP beginning in the 19th century was energized by FF. It is not by chance that the GDP of modern nations remains tightly correlated with petroleum consumption (Figure 2) and that the poorest half of humanity accounts for less than 20% of the global energy use [53].

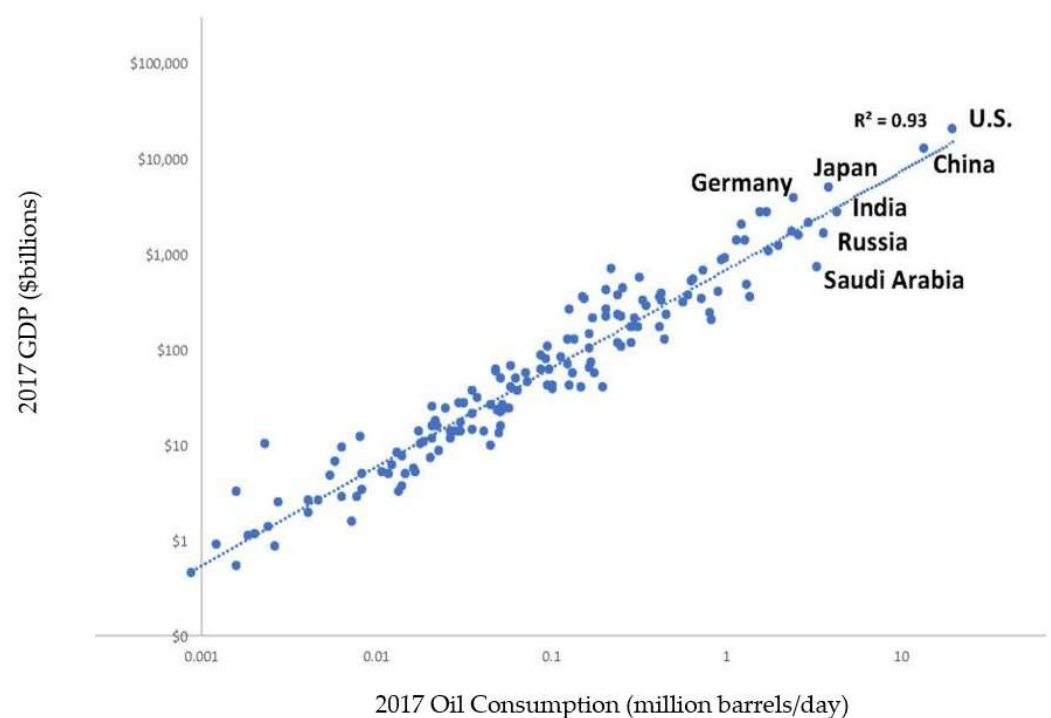


Figure 2. GDP is proportional to oil consumption (Log scales). Graph courtesy of Arthur Berman.

As matters stand, the modern world remains largely dependent on the unmatched energy density of FF. Despite the hyperbole surrounding the rapid development of alternative allegedly renewable energy sources [54], 82% of the world's primary energy was provided by coal, oil, and natural gas in 2021. Non-hydro renewables, mostly wind turbines and solar panels (the recipients of most new investment), provided less than 7.0%. In effect, fossil fuels powered the world economy for 290 of 365 days in 2021 compared with 24 days by all non-hydro renewables (wind, solar, biomass, and geothermal) combined.

Continued fossil fuel dependence is hugely problematic and not just because of climate change. The many components of MTI civilization from individual people and industries, to whole cities and nation states—indeed the entire human enterprise—share the characteristics of ‘dissipative structures’, the term coined by Ilya Prigogine to describe processes

of non-equilibrium self-organization in living systems [55,56]. Dissipative structures develop/evolve in response to energy gradients, which they subsequently ‘dissipate’ (i.e., consume and degrade) to self-produce and maintain themselves. Indeed, self-organization in open systems (systems able to exchange energy and materials with their environments) requires the dissipation of energy.

The human enterprise is a complex of overlapping, highly structured, non-linear, open sub-systems each functioning in far-from-(thermodynamic)-equilibrium. ‘Thermodynamic equilibrium’ describes the state of a system in which there is no structure or gradients and thus no internal flows of matter or energy. Thermodynamic equilibrium can also exist between a system and its environment. In either case, no measurable changes can occur. In contrast, self-producing non-equilibrium systems—e.g., individual living cells, the human body, economic processes—are capable of dynamic change, including net flows between the systems and their environments and the permanent dissipation of energy and matter. Such systems are thus said to be operating ‘far-from-equilibrium’.

As noted, the modern human enterprise has evolved in its present form largely in response to the steep energy gradient represented by fossil fuels which it has been dissipating, on an accelerating curve, particularly over the past two centuries (half the fossil fuels ever consumed have been burned in just the past 30–35 years). It is not only fossil fuels. Fossil-fuelled industrialization has increased the world’s consumption of many minerals and metals by several orders of magnitude, so the best deposits of many finite and non-replenishing non-renewable resources have also been largely depleted and dissipated. Resource scarcity may well accelerate industrial civilization’s descent from overshoot. The continued growth—or even the steady-state operation—of the human enterprise thus depends entirely on the continuity of this energy flow, i.e., on the maintenance of a comparably steep energy gradient (and this assumes other resources will also be available) [57].

However, there is a problem. It is becoming increasingly evident that a quantitatively equivalent energy transition from FFs to so-called green electricity sources on a climate/overshoot friendly schedule is not likely to occur [58–60]. It is true that there has been impressive expansion of electricity generation by wind turbine and solar panel installations in some countries in recent years. However, as noted, FF still provided 82% of the world’s primary energy and even 61% of the world’s electrical power in 2021. Wind turbines and solar installations did give the world 10% of its electrical energy (up to 12% by 2023) but, since electricity is only ~19% of final energy consumption, wind and solar electricity account for only ~2.3% of consumers’ total energy supply, this after several decades of increasing deployment (data from [61]).

Renewable green energy clearly has a long way to go—in some years, additions to renewable capacity do not even keep up with the growth in total demand for energy. As we phase out (or run out) of FF, some analysts suggest that the world community should be preparing for a steep energy descent, a future with markedly lower—as much as 50% lower—and increasingly unreliable energy supplies [62]. The obvious, but often unspoken, corollary is that the weakening of our energy gradient will be accompanied by a massive simplification of that greatest of dissipative structures—the human enterprise. Certainly, there will be a corresponding plunge in GWP (see Figure 2); we should also anticipate global shortages of food and all the other FF-dependent material resources needed to run modern civilization—and we have not yet accounted for the simultaneous consequences of accelerating global heating. Should MTI culture maintain its present course, a major population correction seems inevitable.

5. The World’s Response to Overshoot

“Overshoot is overshoot. Once your civilization starts to consume more than what naturally gets regenerated in its folly to pursue infinite growth on a finite planet, collapse is only a matter of time” (B [63]).

Humanity's evolutionary trajectory and our recent period of industrial expansion have obviously generated a truly unique eco-predicament for humanity—humans are innately expansionist, and MIT culture is growth-addicted, but material growth on a finite planet must eventually cease. The most encouraging sign of awakening to this contradiction is that an international planned 'degrowth' movement is gathering momentum, particularly in Europe [64]. Even members of the European Parliament are openly concerned about the risks associated with continued economic growth [65]. Such concerns are stimulated by increasing numbers of science-based analyses and popular reports that, even without mentioning overshoot, broach the possibility that MTI societies are facing economic and population collapse [66–68].

Societal collapse is a complex controversial subject. There is no consistent definition. However, there is consensus that collapse can be rapid or take decades, but invariably involves a significant loss of socio-political and economic complexity, including the dissolution/replacement of formal governments [69]. Significant population decline is possible even with regional collapses—there is a considerable history of associating collapse with overpopulation and competition for scarce resources [70].

Those who doubt that collapse is a real possibility should remember that many regional human societies have imploded in the past and that MTI societies are now so tightly entangled that the next contraction may well be global. In a rational world, the international community would act cooperatively and decisively in response to evidence of overshoot and organize to eliminate its corrosive impacts. Regrettably, nothing of the kind is occurring. MTI society does not even acknowledge overshoot. On the contrary, most industrialized countries and even the mainstream environmental movement retain their simplistic foci on climate change and both seem determined to find ways of maintaining the perpetual growth trajectory.

Some environmentalists do urge rapid disinvestment from, and the abandonment of, coal, oil, and natural gas. However, aggressive moves to reduce FF use by even the Paris Climate Agreement's minimal 45% by 2030, would constitute political (if not societal) suicide in the absence of viable energy alternatives and a comprehensive socioeconomic restructuring plan backed by public support. Everything in the modern world depends on the continuity of energy supplies. Thus, rapid FF cutbacks would result in economic chaos—reduced goods production, massive unemployment, broken supply chains, failing GDP, declining personal incomes, over-whelmed social services, etc. Food production would plummet; essential marine and diesel-powered inter-city transportation would falter; there would be local famines, mass migrations, and a global food shortage, exacerbated by continuing climate change, civil disorder, and geopolitical chaos. Even if atmospheric GHG concentrations were to stabilize, there is already an additional 0.6 °C warming 'in the pipe' due to short-term feedback such as the thermal inertia of the oceans. This alone will take the world over the 1.5 °C warming limit and further destabilize the climate [71].

All of which helps explain why most of MTI's senior governments, urban administrations, international organizations, many academic analysts, and even environmental organizations have adopted an alternative two-track strategy oriented to maintaining the status quo as follows:

Track 1: Rather than abandoning FFs, governments are maintaining subsidies to FF development: indeed, subsidies in 2022 were double those of the previous year [72]. Consequently, even the International Energy Agency expects that the share of fossil fuels in the global energy mix will remain above 60%, even in 2050 [73]. This will keep our industrial Titanic afloat until Track 2 can be fully realized or until economically extractable FFs are depleted.

Track 2 (running parallel to Track 1): Meanwhile, seduced by the promise of cheap, 100% renewable energy [54], the world has also bought into a new mythic construct, the so-called renewable energy (RE) transition. Under such banners as the 'Green New Deal', the 'circular economy', and the oxymoronic concept of 'green growth', MTI societies are striving to electrify everything and drive investment into so-called renewable green energy

sources, particularly wind turbines, solar panels, and, most recently, hydrogen (none of which are truly green), along with corresponding infrastructure and applications (i.e., electric vehicles). All such ‘approved’ technologies—including as yet unproved carbon capture and storage technologies—involve massive capital investment, significant job creation, and excellent opportunities for profit, i.e., everything necessary to maintain growth-oriented ‘business-as-usual-by-alternative-means’. Arguably, the mainstream MTI approach is designed to make industrial capitalism appear to be the solution to, rather than a cause of, the problem [74].

Regrettably, the overall MTI strategy is ecology-, energy-, material-, and technology-blind—tantamount to ‘Electrifying the Titanic’, as if this would melt the icebergs [75]. As already noted, the much-vaunted green energy transition has arguably barely started and is mired in controversy. See the rebuttals to Seibert and Rees [76] available at: <https://doi.org/10.3390/en14154508> (accessed on 8 August 2023). Its most ebullient proponents ignore important technical issues, ecological and social impacts, and problems stemming from the massive scale of the exercise, i.e., they ignore overshoot. In a nutshell, wind and solar technologies are actually not renewable (merely replaceable); their production from mine-head through manufacturing to installation is itself fossil-energy-intensive; so, the transition, in the best case, will generate at least a short-term bump in carbon emissions; they cannot deliver the same quantity and quality of energy as FFs, and their life-cycles, including orders of magnitude increases in mining and refining activities for certain crucial rare minerals, entail massive ecological degradation and (so far) egregious social injustice [76]. Several authorities have calculated that there are simply not enough economic material deposits or adequate time to replace the existing fossil fuel powered system with renewable technologies on the schedule set by the Intergovernmental Panel on Climate Change reports and advanced by the Paris and subsequent climate Agreements [77,78]. Various climate scientists refer to ‘net zero by 2050’ as involving yet another collection of “magical yet unworkable” technical (non)solutions to the climate conundrum [79] or as “not just a goal, but a strategy for COP-26 to lock in many decades of unnecessary fossil fuels use well past 2050. . . [and creating] unacceptable risks of unstoppable climate warming” [80]. Remember, Track 1 entrenches the FF addiction. Indeed, 50 years after the publication of *Limits to Growth*, several formal ‘scientists’ warnings to humanity’, 27 United Nations COP meetings on climate, and several agreements on emissions reductions, the mainstream approach has so far failed to do anything significant to reduce global FF use and associated emissions. Instead, human-induced global warming rates are at their highest historical level, and the world can expect to reach and exceed the 1.5 °C global warming within the next 10 years [81,82].

In this light, Track 1 of the MTI strategy is potentially catastrophic. Continued use of FF means there is virtually no possibility that the world will achieve the Paris Agreement target to reduce carbon dioxide emissions by 45% from 2010 levels by 2030 and virtually none that the world will reach net zero emissions by 2050. Indeed, the UN reports that current national commitments will actually increase emissions by 10.6% by 2030 [83]. Not only will we blow past the 1.5 °C mean global warming limit of the Paris agreement [84], we are likely to exceed even the less stringent 2.0 °C degree limit by 2050. We are actually on track for 2.4–2.8 degrees warming by century’s end [85]—atmospheric greenhouse gases, including carbon dioxide, are still increasing [86]. Meanwhile, climate change has already put ~9% of people (>600 million) outside the historic safe human climate niche and 2.7 °C global warming could push about one-third of humanity outside the niche [87]. This does not account for threshold effects—even 2 °C warming may well trigger irreversible runaway “hothouse Earth” conditions [88], ending prospects for global civilization. Local ecosystems and possibly the ecosphere as a whole are similarly prone to abrupt, unpredictable irreversible changes that are potentially hostile to human (and other) life, if pushed beyond unknown tipping points [89].

Even under in the best-case scenario, Track 1 leads the world to more and longer heat waves and droughts, more violent tropical storms, extended wildfire seasons, accelerating

desertification, and water shortages. In many respects, 2023 is turning out to be a record-breaking archetypal demonstration of what the future will bring. Many regions on several continents are suffering record heat waves and drought or unprecedented precipitation and floods; and, at the time of writing, over 900 wildfires are raging, most out of control, in the Boreal forests of Canada and many more in the forests of Siberia. As parts of the planet become uninhabitable, we should expect faltering agriculture, food shortages, and possibly extended famines [90]. Rising sea levels over the next century will flood many coastal cities; with the breakdown of national highway and marine transportation networks other cities are likely to be cut off from food-lands, energy, and other essential resources. Some large metropolitan areas will become unsupportable and not survive the century [91]. Even in 2021, at least 414 cities with a total 1.4 billion plus inhabitants, were deemed to be at high or extreme risk from a combination of pollution, dwindling water supplies, extreme heat stress, and other vulnerabilities to climate change alone [92].

Which brings us back to the faltering Track 2 and overshoot. Barring all-out nuclear holocaust, one could argue that the only thing worse than the failure of Track 2's so-called green renewable energy transition would be its success. Developing another assured supply of abundant cheap energy would simply allow for the extension of growth-based 'business-as-usual-by-alternative-means', increasing the depletion/dissipation of the natural world and worsening overshoot:

It is human nature to "...intensify our exploitation of fossil fuels, metals, and non-metallic minerals in order to perpetuate our industrial lifestyle paradigm for as long as possible. . . Paradoxically, the more vigorously we strive to perpetuate our unsustainable industrialized way of life. . . the more quickly and thoroughly we will deplete Earth's remaining non-renewable and renewable reserves, thereby hastening and **exacerbating our global societal collapse**" ([93], emphasis added).

Ironically, then, with the success of the Track 2 mission, the ecosphere would succumb within decades to irreversible degradation, disordering, and dissipation, taking the global human enterprise with it. Arguably, a smaller contraction sooner is preferable to a massive one later.

It Would Not Be the First Time

The prospect of societal collapse, however horrific it sounds to MTI ears, is perfectly consistent with history and the systems dynamics characterizing the rise and fall of previous human civilizations [94,95]. In particular, many MTI nations are exhibiting the diminishing returns and socio-political pathologies—egregious and increasing inequality, government and institutional incompetence and corruption, currency debasement, popular loss of confidence in the state, increasing civil unrest, etc.—of an overly complex society on the verge of collapse [96] as well as the potentially avoidable symptoms—ecological destruction, climate change, breakdown of trade and international relationships, and inability or unwillingness to adapt to changing circumstances—of a society apparently 'choosing' to fail [97].

More generally, the stages of civilizational development and decay catalogued by Toynbee [94] (genesis, growth, time of troubles, universal state, and disintegration) are markedly similar to the phases of the repetitive cycles common to living systems (initiation and exploitation, maturation and conservation, rigidification and release (i.e., collapse)). Gunderson and Holling advance the 'panarchy' theory to explore such cyclical change as a mechanism for adaptation common to complex ecosystems and social systems. They argue that each iteration of a naturally-repeating cycle (e.g., the cyclical fire regime of certain forest ecosystems) theoretically provides opportunities for innovation and evolutionary adaptation [98]. One is forced to wonder why modern *H. sapiens* stubbornly fail to apply lessons from well-studied historic collapses to develop the foresight and the policy actions needed to head off the next.

On the contrary, many analysts reject historical precedents as guides to contemporary policy. Perhaps they should take warning from the aforementioned infamous 1972 Club of Rome/MIT study, *Limits to Growth* (LTG) [99], which showed that, on a business-as-usual

track, global society would face collapse by mid-21st century. As might be expected, many economists and techno-optimists roundly rejected this assessment—economists ignore overshoot and even grossly underestimate the damage from climate change; their concepts and models are divorced from biophysical reality [100]. However, subsequent studies show that the real world is behaving with disturbing fidelity to LTG modelling, particularly the two (of four) scenarios that indicate a halt in growth over the next decade or so, followed by subsequent declines and collapse [101].

6. Summary and Conclusions: It's Really Quite Simple

“Without a biosphere in a good shape, there is no life on the planet. It's very simple. That's all you need to know. The economists will tell you we can decouple growth from material consumption, but that is total nonsense. . . If you don't manage decline, then you succumb to it and you are gone” (Vaclav Smil, [102]).

H. sapiens, like all other species, are naturally predisposed to grow, reproduce, and expand into all suitable accessible habitat. Physical growth is natural, but is only an early phase in the development of individual organisms; growth in sheer scale, including population growth, is characteristic of early phases of complex living systems, including human societies. However, both material and population growth in finite habitats are ultimately limited by the availability of essential ‘inputs’, by the capacity of the system's environment to assimilate (often toxic) outputs, or by various forms of negative feedback as previously listed. Growth will cease, either by “design or disaster” [103]

For most of *H. sapiens*' evolutionary history, local population growth has, in fact, been constrained by negative feedback. However, improved population health (lower death rates) and the use of fossil fuels, particularly since the early 19th century, enabled a period of unprecedented food and resource abundance. In nature, any ‘K’-strategic species population enjoying such favourable conditions will expand exponentially. Growth will generally continue until excess consumption and habitat degradation once again lead to food shortages and starvation, or disease and predation take their toll. The population then falls back below the long-term carrying capacity of the habitat and negative feedback eases off. Some species repeatedly exhibit this cycle of population boom and bust.

Humanity is only a partial exception. The abundance generated by fossil fuels enabled *H. sapiens*, for the first time, to experience a one-off global population boom—bust cycle (Figure 1). It is a ‘one-off’ cycle because it was enabled by vast stocks of both potentially renewable self-producing resources and finite non-renewable resources, including fossil fuels, which have been greatly depleted. No repetition is possible. As Clugston argues, by choosing to industrialize, *Homo sapiens* unwittingly made a commitment to impermanence [77]. We adopted a self-terminating way of life, in which the finite resources that enable our industrial existence would inevitably become insufficient to do so.

The physical mechanisms are simple. Living systems, from individual cells through whole organisms to populations and ecosystems, exist in nested hierarchies and function as far-from-equilibrium dissipative structures [104]. Each level in the hierarchy depends on the next level up both as a source for useful resources (negentropy) and as a sink for degraded wastes (entropy). As Daly [8,9] reminds us, the human enterprise is a wholly-dependent subsystem of the ecosphere; it produces and maintains itself by extracting negentropic resources from its host system, the ecosphere, and dumping degraded entropic wastes back into its host. It follows that the increasing structural and functional complexity of the human sub-system as a far-from equilibrium-dissipative structure (a node of negentropy) can occur only at the expense of the accelerated disordering (increasing entropy) of the non-growing ecosphere. Indeed, humanity is in overshoot—global heating, plunging biodiversity, soil/land degradation, tropical deforestation, ocean acidification, fossil fuel and mineral depletion, the pollution of everything, etc., are indicative of the increasing disordering of the biosphere/ecosphere. We are at risk of a chaotic break-down of essential life-support functions [105].

Little of this is reflected in contemporary development debates or in discussions of the population conundrum. The international community's response to incipient biospheric collapse is doubly disastrous. MTI culture's commitment to material growth, including continued FF use (Track 1), condemns humanity to the predictably dangerous impacts of accelerating climate change; at the same time, our pursuit of alternative energy sources (themselves FF dependent) in order to maintain the growth-based status quo (Track 2) would, if successful, assure the continued depletion and dissipation of both self-producing and non-renewable resources essential for the existence of civilization.

The mainstream view of population asserts that the growth rate is declining so "not to worry"—or worry that population decline is bad for the economy! Even the base assertion is controversial. Jane O'Sullivan points out that the rate of decline has itself declined in this century. She argues that UN demographers have thus 'persistently underestimated recent global population, due to their over-anticipation of fertility declines in high-fertility countries' [106]. The human population continues to grow at about 80 million per year—O'Sullivan argues that the number is closer to 90 million—and its ultimate peak is highly uncertain. Renewed negative feedback may well end growth well before the population reaches the UN's expected 10.4 billion in the late 2080s.

It is crucial to remember that, right or wrong, conventional projections ignore the fact that the ecosphere is not actually now 'supporting' even the present eight billion people. The human enterprise is growing and maintaining itself by liquidating and polluting essential ecosystems and material assets. In short, even average material living standards are corrosively excessive, yet, in 2019, 'almost a quarter of the global population... lived below the US\$3.65 per day poverty line, and almost half, 47 percent, lived below the US\$6.85 poverty line' [107] and the world considers sheer material growth as the means to address this problem. Following this path, eco-destruction will ramp up, increasing the probability of a self-induced simplification and contraction of the human enterprise.

Barring a nuclear holocaust, it is unlikely that *H. sapiens* will go extinct. Wealthy, technologically advanced nations potentially have more resilience and may be insulated, at least temporarily, from the worst consequences of global simplification [108]. That said, rebounding negative feedbacks—climate chaos, food and other resource shortages, civil disorder, resource wars, etc.—may well eliminate prospects for an advanced world-wide civilization. In the event of a seemingly inevitable global population 'correction', human numbers will fall to the point where survivors can once again hope to thrive within the (much reduced) carrying capacity of the Earth. Informed estimates put the long-term carrying capacity at as few as 100 million [109] to as many as three billion people [110].

It is uncertain whether much or any of industrial high-tech can persist in the absence of abundant cheap energy and rich resource reserves, most of which will have been extracted, used, and dissipated. It may well be that the best-case future will, in fact, be powered by renewable energy, but in the form of human muscle, draft horses, mules, and oxen supplemented by mechanical water-wheels and wind-mills. In the worst case, the billion (?) or so survivors will face a return to stone-age life-styles. Should this be humanity's future, it will not be urban sophisticates that survive but rather the pre-adapted rural poor and remaining pockets of indigenous peoples.

Bottom line: Any reasonable interpretation of previous histories, current trends, and complex systems dynamics would hold that global MTI culture is beginning to unravel and that the one-off human population boom is destined to bust. *H. sapiens'* innate expansionist tendencies have become maladaptive. However, far from acknowledging and overriding our disadvantageous natural predispositions, contemporary cultural norms reinforce them. Arguably, in these circumstances, wide-spread societal collapse cannot be averted—collapse is not a problem to be solved, but rather the final stage of a cycle to be endured. Global civilizational collapse will almost certainly be accompanied by a major human population 'correction'. In the best of all possible worlds, the whole transition might actually be managed in ways that prevent unnecessary suffering of millions (billions?) of people, but this is not happening—and cannot happen—in a world blind to its own predicament.

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