PERSPECTIVE

Human domination of the biosphere: Rapid discharge of the earth-space battery foretells the future of humankind

John R. Schramski[a,1], David K. Gattie[a], and James H. Brown[b,1]

[a]*College of Engineering, University of Georgia, Athens, GA 30602; and* [b]*Department of Biology, University of New Mexico, Albuquerque, NM 87131*

Edited by B. L. Turner, Arizona State University, Tempe, AZ, and approved June 8, 2015 (received for review May 4, 2015)

Earth is a chemical battery where, over evolutionary time with a trickle-charge of photosynthesis using solar energy, billions of tons of living biomass were stored in forests and other ecosystems and in vast reserves of fossil fuels. In just the last few hundred years, humans extracted exploitable energy from these living and fossilized biomass fuels to build the modern industrial-technological-informational economy, to grow our population to more than 7 billion, and to transform the biogeochemical cycles and biodiversity of the earth. This rapid discharge of the earth's store of organic energy fuels the human domination of the biosphere, including conversion of natural habitats to agricultural fields and the resulting loss of native species, emission of carbon dioxide and the resulting climate and sea level change, and use of supplemental nuclear, hydro, wind, and solar energy sources. The laws of thermodynamics governing the trickle-charge and rapid discharge of the earth's battery are universal and absolute; the earth is only temporarily poised a quantifiable distance from the thermodynamic equilibrium of outer space. Although this distance from equilibrium is comprised of all energy types, most critical for humans is the store of living biomass. With the rapid depletion of this chemical energy, the earth is shifting back toward the inhospitable equilibrium of outer space with fundamental ramifications for the biosphere and humanity. Because there is no substitute or replacement energy for living biomass, the remaining distance from equilibrium that will be required to support human life is unknown.

energy | evolutionary biology | earth-space battery | sustainability | thermodynamics

As depicted in Fig. 1, earth is a battery of stored chemical energy where the planet is the cathode (stored organic chemical energy) and space is the anode (equilibrium). We call this the earth-space battery. It took hundreds of millions of years for photosynthetic plants to trickle-charge the battery, gradually converting diffuse low-quality solar energy to high-quality chemical energy stored temporarily in the form of living biomass and more lastingly in the form of fossil fuels: oil, gas, and coal. In just the last few centuries—an evolutionary blink of an eye—human energy use to fuel the rise of civilization and the modern industrial-technological-informational society has discharged the earth-space battery, inducing flow between the terminals, degrading the high quality biomass energy to do the work of transforming the earth for human benefit, and radiating the resulting low-quality heat energy to deep space.

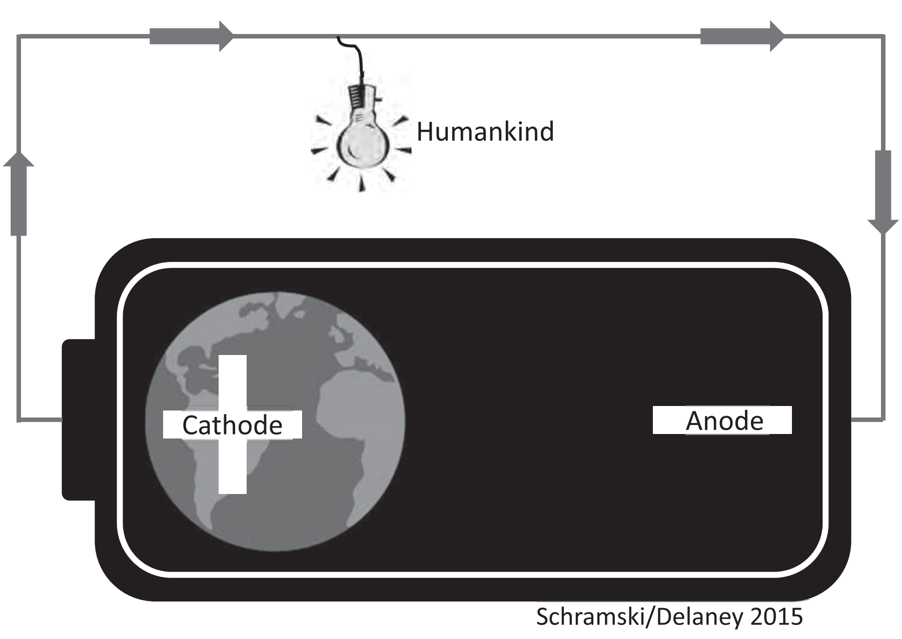

Fig. 1. Earth-space battery. The planet is a positive charge of stored organic chemical energy (cathode) in the form of biomass and fossil fuels. As this energy is dissipated by humans, it eventually radiates as heat toward the chemical equilibrium of deep space (anode). The battery is rapidly discharging without replenishment.

The laws of thermodynamics dictate that the difference in rate and timescale between the slow trickle-charge and rapid depletion is unsustainable. The current massive discharge is rapidly driving the earth from a biosphere teeming with life and supporting a highly developed human civilization toward a barren moonscape. Consider as an example that the energy state of the earth is akin to the energy state of a house powered by a once-charged battery supplying all energy for lights, heating,

Author contributions: J.R.S. and D.K.G. designed research; J.R.S. and J.H.B. performed research; J.R.S. and J.H.B. contributed new reagents/analytic tools; J.R.S., D.K.G., and J.H.B. analyzed data; and J.R.S., D.K.G., and J.H.B. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

[1]To whom correspondence may be addressed. Email: jschrams@uga.edu or jhbrown@unm.edu.

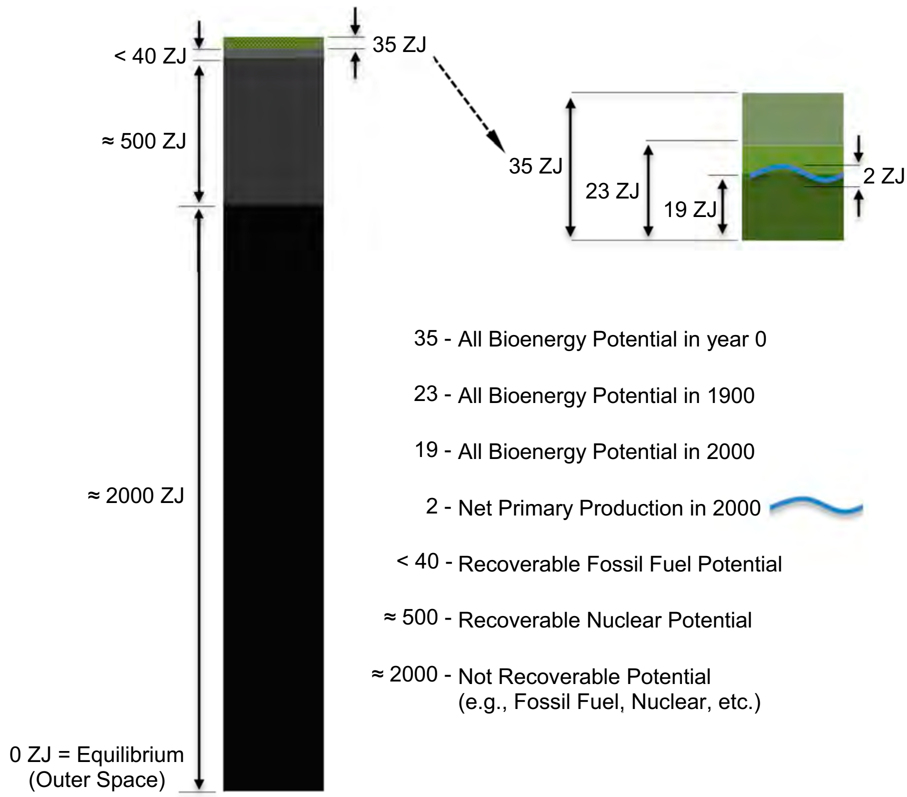

Fig. 2. Earth chemical and nuclear energy storage (distance from equilibrium) (10, 11, 38, 39). Where necessary, biomass is converted to energy assuming 1 t carbon ~35×10^9 joules. ZJ = zeta joules = joules × 10^{21}.

cooling, cooking, power appliances, and electronic communication; as the battery discharges, these services become unavailable and the house soon becomes uninhabitable.

Energy in Physics and Biology

The laws of thermodynamics are incontrovertible; they have inescapable ramifications for the future of the biosphere and humankind. We begin by explaining the thermodynamic concepts necessary to understand the energetics of the biosphere and humans within the earth-space system. The laws of thermodynamics and the many forms of energy can be difficult for nonexperts. However, the earth's flows and stores of energy can be explained in straightforward terms to understand why the biosphere and human civilization are in energy imbalance. These physical laws are universal and absolute, they apply to all human activities, and they are the universal key to sustainability.

Energy is how far a property (e.g., temperature, chemical, pressure, velocity) is from equilibrium. This distance, or gradient, can be harvested to perform work, in the process moving the property closer to equilibrium. Thus, whereas the capacity to perform work is often used as the simplest definition of energy, ultimately this capacity requires an out-of-equilibrium system, a gradient, which is available to be harvested. For example, the earth is out of chemical equilibrium with respect to nearby space; as we burn fossilized chemical energy to get work output, the earth loses the resultant heat and moves closer to equilibrium. Similarly, when we burn living biomass faster than the earth can replenish it, the earth again moves closer to equilibrium. The first Law of Thermodynamics assures that, although energy is transformed between solar, chemical, work, and heat in these transactions, it is neither created nor destroyed; it changes forms, but the total quantity is conserved. The Second Law of Thermodynamics assures that as energy changes forms, all of this energy is eventually degraded to low-quality heat energy and lost from the planet. These physical laws not only have allowed the evolution of life, they also have allowed the development of human civilization. Living things use photosynthesis to convert diffuse but reliable sunlight into energy-rich organic compounds, and they use respiration to break down these compounds, release the stored energy, and do the biological work of living (1, 2). For humans this means consuming food and respiring to fuel biological metabolism. However, humans also use technological innovations to burn organic chemicals and use this extrametabolic energy to do the additional work of fueling complex socioeconomic activities.

Over the millennia of evolutionary time, as living things evolved, they gradually transformed the earth from a barren planet into a biosphere teeming with life. Until the origin of life, there were no significant stores of organic chemical energy, and the surface of the planet was not far from the chemical equilibrium of the adjacent outer space. Then, as living things evolved and diversified, they developed new biochemical pathways for converting solar energy into biomass. It took on the order of 1 billion years for the first photosynthetic and chemosynthetic prokaryotes to exploit the small energy gradients available and synthesize enough biomass to begin to charge the earth-space's chemical battery. Ancient unicellular organisms created a modest chemical energy gradient that persisted for billions of years. Then starting about 600 Mya, with the Cambrian explosion of diversity of large multicellular organisms and the subsequent colonization of land by plants, the biosphere acquired a large store of living biomass, mostly in the form of forests (3). In the Carboniferous, Permian, and Jurassic periods (350–150 Mya), remains of dead plants and animals were preserved in the earth's crust to create the reserves of coal, oil, and gas. Since then, the earth has mostly been in an energetic quasi-equilibrium, continually perturbed by asteroid impacts, tectonic activity, glaciations, and climatic fluctuations, modestly adding to or subtracting from the stores of fossil fuels, but always returning to an approximate balance between solar input and heat loss, photosynthesis, and heterotrophic metabolism.

Everything changed when anatomically modern humans appeared and expanded out of Africa to colonize the entire Earth. The most important milestone was the development and spread of agriculture, which began about 12,000 y ago. Before this, hunter-gatherer societies had been in approximate equilibrium, relying on photosynthetic energy to supply plant and animal foods and fuels for cooking and heating and barely altering the Earth's surface. With the advent of agriculture, humans began systematically to harvest the stored biomass gradient and to increase chemical energy discharge. Initially, human and animal labor and fires of wood and dung were used to do the work of manufacturing tools, clearing land, tilling fields, and harvesting crops. However, ever more inventive societies developed new technologies based on harnessing new energy sources. Most importantly, the industrial revolution used wind and water mills to do work and burned first wood, then charcoal, and finally fossil fuels to mine and smelt metal ores and to manufacture tools and machines. These developments led to ever-larger human populations with ever-more complex economies and social systems, all fueled by an ever-increasing rate of chemical energy discharge.

The Paradigm of the Earth-Space Battery

By definition, the quantity of chemical energy concentrated in the carbon stores of planet Earth (positive cathode) represents the distance from the harsh thermodynamic equilibrium of nearby outer space (negative anode). This energy gradient sustains the biosphere and human life. It can be modeled as a once-charged battery. This earth-space chemical battery (Fig. 1) trickle charged very slowly over 4.5 billion years of solar influx and accumulation of living biomass and fossil fuels. It is now discharging rapidly due to human activities. As we burn organic chemical energy, we generate work to grow our population and economy. In the process, the high-quality chemical energy is transformed into heat and lost from the planet by radiation into outer space. The flow of energy from cathode to anode is moving the planet rapidly and irrevocably closer to the sterile chemical equilibrium of space.

Fig. 2 depicts the earth's primary higher-quality chemical and nuclear energy storages as their respective distances from the equilibrium of outer space. We follow the energy industry in focusing on the higher-quality pools and using "recoverable energy" as our point of reference, because many deposits of fossil fuels and nuclear ores are dispersed or inaccessible and cannot be currently harvested to yield net energy gain and economic profit (4). The very large lower-quality pools of organic energy including carbon compounds in soils and oceanic sediments (5, 6) are not shown, but these are not currently economically extractable and usable, so they are typically not included in either recoverable or nonrecoverable categories. Although the energy gradients attributed to geothermal cooling, ocean thermal gradients, greenhouse air temperatures, etc., contribute to Earth's thermodynamic distance from the equilibrium of space, they are also not included as they are not chemical energies and presumably would still exist in some form on a planet devoid of living things, including humans. Fig. 2 shows that humans are currently discharging all of the recoverable stores of organic chemical energy to the anode of the earth-space battery as heat.

The organism-generated earth-space battery consists of two kinds of organic chemical compounds. The first are fossil fuels. These fossil fuels are primarily hydrocarbons, containing mostly carbon and hydrogen, almost no oxygen, and often small but significant amounts of other elements, such as sulfur, vanadium, iron, zinc, and mercury, which can be toxic when released into the environment and taken up by humans and other organisms. The reserves of fossil fuels, most deposited hundreds of millions of years ago, are finite and rapidly being depleted. Oil, gas, and coal, which account for more than 85% of current global human energy consumption, are burned to produce the goods and services for our industrial-technological-informational economy. Despite some excellent sobering analyses of the present use and future prospects of fossil fuels (4, 7, 8), the magnitude of the remaining economically recoverable hydrocarbon energy store is subject to much debate. In Fig. 2 we acknowledge the uncertainty by assigning a conservative value of <40 zeta joules (ZJ).

The Critical Importance of Living Biomass

Here we focus on the second kind of chemicals comprising the earth-space battery, the organic compounds in living biomass. Our work suggests that the two smallest values, 19 and 2 ZJ, on the bar chart in Fig. 2 are the most important. The 19 ZJ represents the current chemical potential energy stored in the form of living biomass, most of it as phytomass in terrestrial plants and most of that in forests. These chemicals are the carbohydrates, lipids, proteins, cellulose, lignins, and other substances that make up the bodies of living organisms. Unlike fossil fuels, the magnitude of this energy storage gradient (i.e., its distance from equilibrium) is maintained by a steady flow of solar energy (9). The 2 ZJ is the energy flow due to the net annual primary production (NPP) of the planet, which is the quantity of energy converted each year from solar energy to biomass by the process of photosynthesis. Global NPP is the Earth's yearly renewable energy budget within which all living things operate and within which our hunter-gatherer human ancestors previously operated. Therefore, an input of 2 ZJ/y of photosynthesis maintains a standing stock of 19 ZJ of stored biomass.

This stored biomass is essential to modern humans, because its chemical energy sustains a habitable biosphere away from the chemical equilibrium of space. The NPP and stored living biomass of the biosphere maintain biodiversity and regulate climate and biogeochemical cycling. The metabolic energy that powers our bodies and sustains our population is derived from NPP, because all of our food is living biomass produced by the plants and animals in the earth's diverse ecosystems: agricultural fields, grazing lands, oceans, and fresh waters. Furthermore, biomass is essential for humans to access all other forms of energy, including wind, hydro, fossil, nuclear, etc.

Living Biomass Is Depleting Rapidly

At the time of the Roman Empire and the birth of Christ, the earth contained ∼1,000 billion tons of carbon in living biomass (10), equivalent to 35 ZJ of chemical energy, mostly in the form of trees in forests. In just the last 2,000 y, humans have reduced this by about 45% to ∼550 billion tons of carbon in biomass, equivalent to 19.2 ZJ. The loss has accelerated over time, with 11% depleted just since 1900 (Fig. 3) (11, 12). Over recent years, on average, we are harvesting—and releasing as heat and carbon dioxide—the remaining 550 billion tons of carbon in living biomass at a net rate of ∼1.5 billion tons carbon per year (13, 14). The cause and measurement of biomass depletion are complicated issues, and the numbers are almost constantly being reevaluated (14). The depletion is due primarily to changes in land use, including deforestation, desertification, and conversion of vegetated landscapes into barren surfaces, but also secondarily to other causes such as pollution and unsustainable forestry and fisheries. Although the above quantitative estimates have considerable uncertainty, the overall trend and magnitude are inescapable facts with dire thermodynamic consequences.

The Dominant Role of Humans

***Homo sapiens* Is a Unique Species.** The history of humankind—starting with hunter-gatherers, who learned to obtain useful heat energy by burning wood and dung, and continuing to contemporary humans, who apply the latest technologies, such as fracking, solar panels, and wind turbines—is one of innovating to use all economically exploitable energy sources at an ever increasing rate (12, 15). Together, the biological imperative of the Malthusian-Darwinian dynamic to use all available resources and the social imperative to innovate and improve human welfare have resulted in at least 10,000 y of virtually uninterrupted population and economic growth: from a few million hunter-gatherers to more than 7 billion modern humans and from a subsistence economy based on sustainable use of plants and animals (i.e., in equilibrium with photosynthetic energy production) to the modern industrial-technological-informational economy (i.e., out of equilibrium due to the unsustainable unidirectional discharge of the biomass battery).

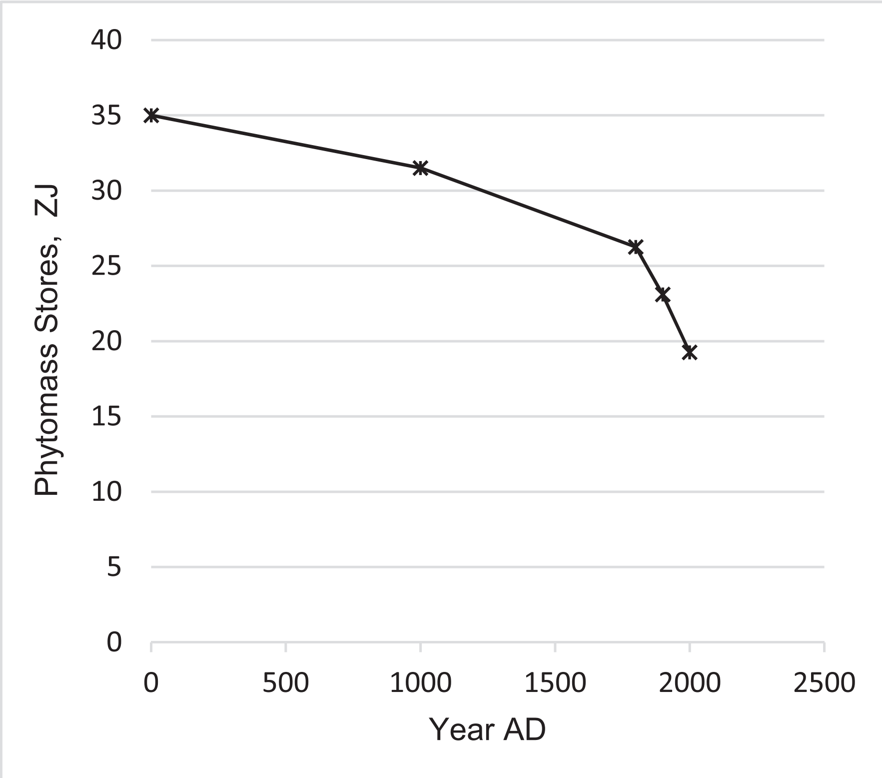

Fig. 3. Global phytomass stores. Calculated from table 2 of Smil (11), assuming 1 t carbon ~35×10^9 joules. ZJ = zeta joules = joules $\times$ 10^{21}.

Fig. 4 depicts the multiplier effect of two large numbers that determine the rapid discharge rate of the earth-space battery. Energy use per person multiplied by population gives total global energy consumption by humans. According to British Petroleum's numbers (16), which most experts accept, in 2013, average per capita energy use was 74.6×10^9 J/person per year (equivalent to ~2,370 W if plotted in green in Fig. 4). Multiplying this by the world population of 7.1 billion in 2013 gives a total consumption of ~0.53 ZJ/y (equivalent to 16.8 TW if plotted in red in Fig. 4), which is greater than 1% of the total recoverable fossil fuel energy stored in the planet (i.e., 0.53 ZJ/40 ZJ = 1.3%). As time progresses, the population increases, and the economy grows, the outcome of multiplying these two very large numbers is that the total rate of global energy consumption is growing at a near-exponential rate.

To put these numbers in perspective, consider a point of reference. An individual human requires on average 8.4 MJ/d (2,000 kcal/d) in the form of food to support a biological metabolic rate of about 100 W. To fuel their diverse activities, contemporary humans supplement biological metabolism with extrametabolic energy derived from other sources, principally fossil fuels. Therefore, the current per-capita consumption of 2,370 W identified above for an average person is about 24 times that of a hunter-gatherer ancestor. Furthermore, this average value does not indicate the wide variation in per capita energy consumption as a function of socioeconomic conditions, which ranges from only slightly more than the biological metabolic rate in the poorest developing countries to more than 11,000 W in the most developed countries with their energy-demanding industrial-technological-informational economies (8, 17). Compared with humankind's metabolic needs and the remaining chemical stores in the earth-space battery (distance to thermodynamic equilibrium), the rate of net discharge is very large and obviously unsustainable.

The earth is in serious energetic imbalance due to human energy use. This imbalance defines our most dominant conflict with nature. It really is a conflict in the sense that the current energy imbalance, a crisis unprecedented in Earth history, is a direct consequence of technological innovation. The detrimental effects of discharging the organic chemical energy stored in the battery extend far beyond the depletion of stored living phytomass and fossil fuel energy. Consider minerals. Energetically overpowered humans have discovered and mined most of the richest deposits of copper, iron, zinc, gold, and silver, used these metals to support the industrial economy, and dispersed the unused "wastes" to landfills and unrecoverable pools. Consider nitrogen and phosphorus, critical ingredients of fertilizer because they are essential for plant growth. Global deposits of nitrate and phosphate have been drastically depleted. Nitrogen fertilizer can be synthesized from atmospheric nitrogen gas, but this chemical process requires a large input of exogenous energy, usually in the form of fossil fuel (18). More ominously, there is no substitute for or mechanism for artificially synthesizing phosphorus. Consider water. By damming rivers and streams and digging wells into subsurface aquifers, humans currently use more than 56% of all accessible fresh water. Most of this water is used for irrigation of crops, so that human activities account for about 26% of the water lost by evapotranspiration from terrestrial ecosystems (19, 20). Consider impacts on global ecosystems (21) and biodiversity (22). To produce plant and animal products for human consumption and to house our growing population, we have transformed ecosystems and landscapes on approximately 83% of Earth's ice-free land area. We have replaced forests and other native ecosystems with agricultural crops, pastures, forestry plantations, buildings, and pavement, pre-empting about 40% of terrestrial NPP and reducing the standing stock of living biomass on the planet by an estimated 45%. Additional human-caused changes have substantially reduced the stocks of ocean fisheries, altered global biogeochemical cycles and climate, and caused extinction of species at 100–1,000 times the average prehuman extinction rates. Finally, consider that 15–30% of current global energy consumption is used to simply supply food for 7.2 billion people (23, 24). Most of this energy comes from fossil fuels and is used for the supplemental inputs of water, fertilizer, pesticides, and machine labor that enable modern agriculture to achieve high yields (25–27). Therefore, the human population is sustained by the NPP of agriculture, but the capacity of this agriculture to feed the global population requires massive discharge of the earth-space battery.

The unidirectional dissipation of living biomass and fossil fuel energy from the battery has provided our species unprecedented powerful domination over the biogeochemical cycles and other organisms of the planet. Others have chronicled these changes and their consequences (18–22, 28–30), but their warnings have failed to arouse sufficient public concern and motivate a meaningful response.

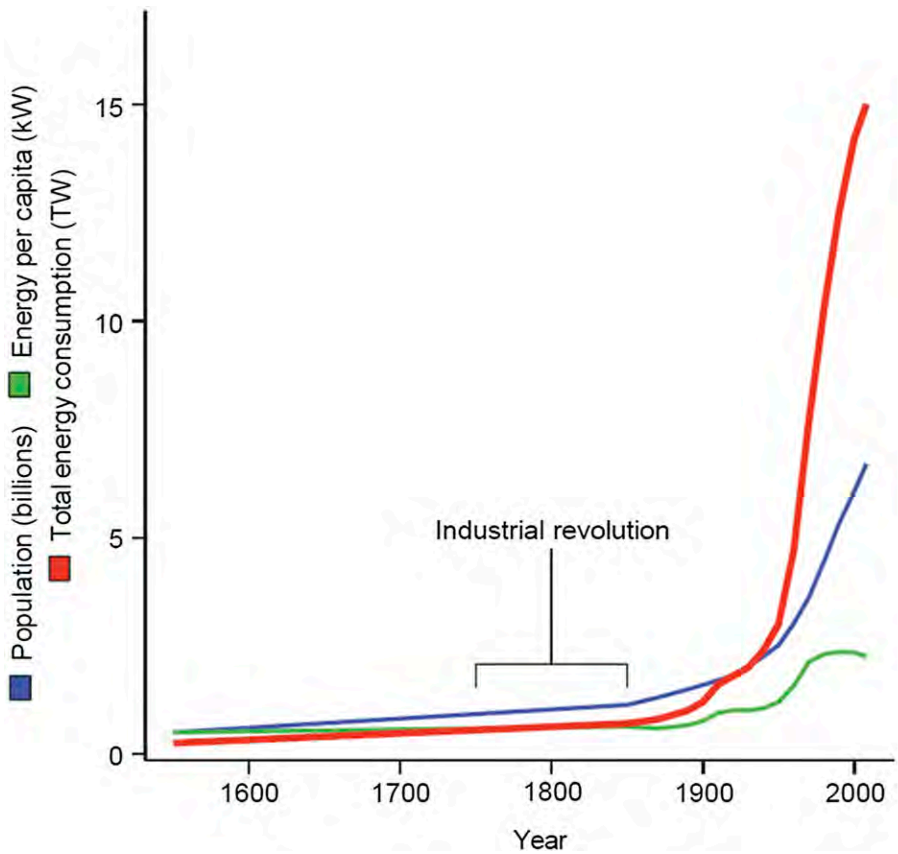

Fig. 4. History of global growth in per capita energy consumption, population, and total energy consumption. Reproduced from ref. 30, with permission from Macmillan Publishers Ltd, *Nature*.

Ironically, powerful political and market forces, rather than acting to conserve the remaining charge in the battery, actually push in the opposite direction, because the pervasive efforts to increase economic growth will require increased energy consumption (4, 8). Much of the above information has been presented elsewhere, but in different forms (e.g., in the references cited). Our synthesis differs from most of these treatments in two respects: (*i*) it introduces the paradigm of the earth-space battery to provide a new perspective, and (*ii*) it emphasizes the critical importance of living biomass for global sustainability of both the biosphere and human civilization.

Humans and Phytomass

We can be more quantitative and put this into context by introducing a new sustainability metric Ω

$$\Omega = \frac{P}{BN} \quad [1]$$

which purposefully combines perhaps the two critical variables affecting the energy status of the planet: total phytomass and human population. Eq. **1** accomplishes this combination by dividing the stored phytomass chemical energy P (in joules) by the energy needed to feed the global population for 1 y (joules per year; Fig. 5). The denominator represents the basic (metabolic) energy need of the human population; it is obtained by multiplying the global population N by their per capita metabolic needs for 1 y ($B = 3.06 \times 10^9$ joules/person·per year as calculated from an 8.4×10^6 joules/person·day diet). The simple expression for Ω gives the number of years at current rates of consumption that the global phytomass storage could feed the human race. By making the conservative but totally unrealistic assumption that all phytomass could be harvested to feed humans (i.e., all of it is edible), we get an absolute maximum estimate of the number of years of food remaining for humankind. Fig. 5 shows that over the years 0–2000, Ω has decreased predictably and dramatically from 67,000 to 1,029 y (for example, in the year 2000, $P = 19.3 \times 10^{21}$ joules, $B = 3.06 \times 10^9$ joules/person·per year, and $N = 6.13 \times 10^9$ persons; thus, Ω = 1,029 y). In just 2,000 y, our single species has reduced Ω by 98.5%.

The above is a drastic underestimate for four reasons. First, we obviously cannot consume all phytomass stores for food; the preponderance of phytomass runs the biosphere. Second, basing our estimate on human biological metabolism does not include that high rate of extrametabolic energy expenditure currently being used to feed the population and fuel the economy. Third, the above estimate does not account that both the global human population and the per-capita rate of energy use are not constant, but increasing at near-exponential rates. We do not attempt to extrapolate to predict the future trajectories, which must ultimately turn downward as essential energy stocks are depleted. Finally, we emphasize that not only has the global store of phytomass energy decreased rapidly, but more importantly human dominance over the remaining portion has also increased rapidly. Long before the hypothetical deadline when the global phytomass store is completely exhausted, the energetics of the biosphere and all its inhabitant species will have been drastically altered, with profound changes in biogeochemical function and remaining biodiversity. The very conservative Ω index shows how rapidly land use changes, NPP appropriation, pollution, and other activities are depleting phytomass stores to fuel the current near-exponential trajectories of population and economic growth. Because the Ω index is conservative, it also emphasizes how very little time is left to make changes and achieve a sustainable future for the biosphere and humanity. We are already firmly within the zone of scientific uncertainty where some perturbation could trigger a catastrophic state shift in the biosphere and in the human population and economy (31). As we rapidly approach the chemical equilibrium of outer space, the laws of thermodynamics offer little room for negotiation.

Discussion

The trajectory of Ω shown in Fig. 5 has at least three implications for the future of humankind. First, there is no reason to expect a different trajectory in the near future. Something like the present level of biomass energy destruction will be required to sustain the present global population with its fossil fuel-subsidized food production and economy. Second, as the earth-space battery is being discharged ever faster (Fig. 3) to support an ever larger population, the capacity to buffer changes will diminish and the remaining energy gradients will experience increasing perturbations. As more people depend on fewer available energy options, their standard of living and very survival will become increasingly vulnerable to fluctuations, such as droughts, disease epidemics, social unrest, and warfare. Third, there is considerable uncertainty in how the biosphere will function as Ω decreases from the present Ω = ∼1,029 y into an uncharted

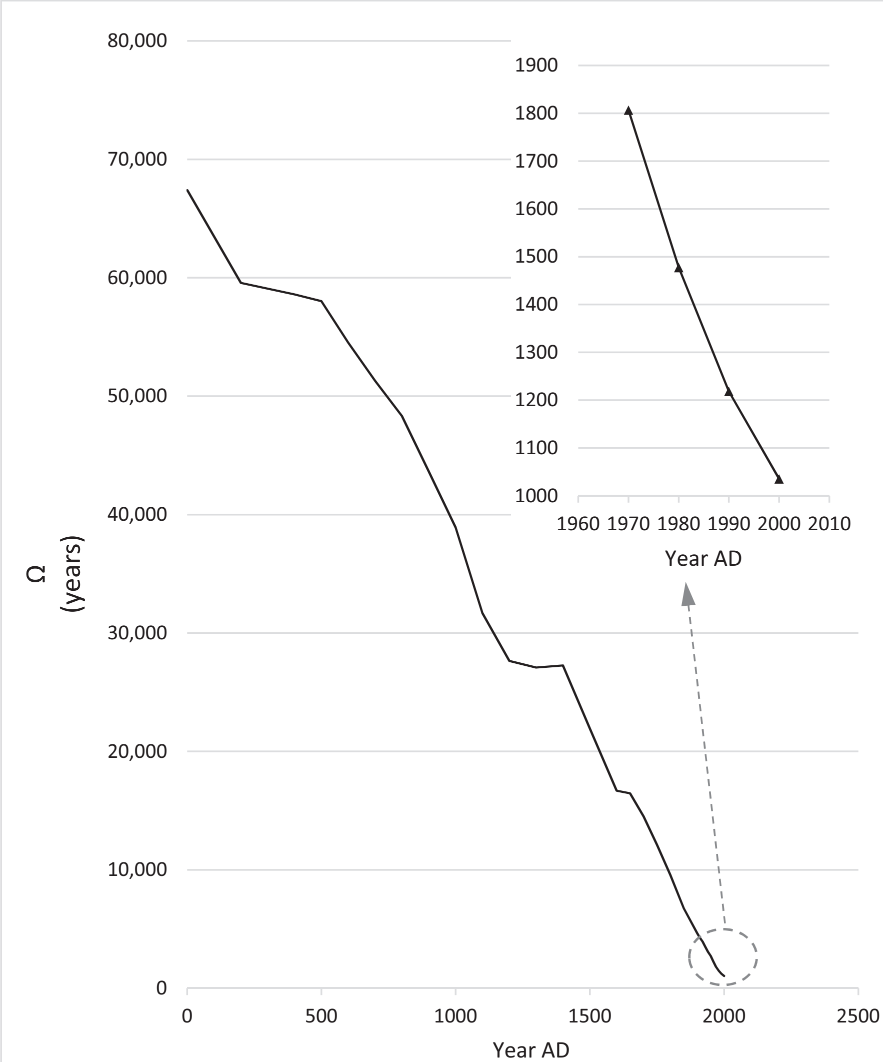

Fig. 5. Number of years of phytomass food potentially available to feed the global human population. Calculated from the total stored phytomass energy of the planet divided by the metabolic energy needs to feed the global population for 1 y (i.e., joules/joules per year = years) assuming an 8.4-MJ per capita daily diet for the entire year. Rapidly decreasing trend line indicates increasing dominance of phytomass by humankind. For reasons given in the text, these values are very conservative. Little margin remains to safely continue the current trend.

thermodynamic operating region. The global biosphere, human population, and economy will obviously crash long before $\Omega = 1$ y. If *H. sapiens* does not go extinct, the human population will decline drastically as we will be forced to return to making a living as hunter-gatherers or simple horticulturalists. Also, the earth after the collapse of human civilization will be a very different place than the biosphere that supported the rise of civilization. There will be a long-lasting legacy of altered climate, landscapes, and biogeochemical cycles, depleted and dispersed stocks of fossil fuels, metals, and nuclear ores, and diminished biodiversity. The most powerful species in the 3.5-billion-year history of life has transformed the earth and left a mark that will endure long after its passing.

Many of the organizations and authors who have recognized the seriousness of the looming energy crisis are suggesting the possibility of achieving some level of sustainability of the global population and economy by implementing renewable energy technologies (32, 33). We too recognize the importance of solar and other renewables in cushioning the ecological and socioeconomic consequences as the biosphere returns toward a steady state between NPP and respiration. There is indeed a large supply of solar energy that has not yet been tapped for human use. As mentioned above, sunlight is highly dispersed low-quality energy. Consequently, current technologies rely heavily on fossil fuels to design, mine, build, and operate the collection and distribution systems (34) and expand the yet to be designed but compulsory large-scale energy storage systems. Moreover, whereas some deployment of solar systems (e.g., over roofs, roads, and parking lots) causes little direct reduction of biomass, greater deployment will undoubtedly result in increasing indirect biomass consequences to both fabricate and install solar collectors and other infrastructure. The earth-space battery paradigm clarifies why the total upfront and ongoing energy investments in solar and other renewables need to be balanced with the energy produced, i.e., greater energy return on energy investment (4, 35), and why their production and installation must not negatively impact the remaining biomass budget of earth.

The logic presented above is indisputable, because the laws of thermodynamics are absolute and inviolate. Unless phytomass stores stabilize, human civilization is unsustainable. The battery paradigm highlights the need to continue to refine estimates of the global biomass degradation (13) and its corresponding chemical energy contents and of recoverable fossil fuels. It emphasizes the need for greater recognition of the central importance of living biomass and the past, present, and future trajectory of decreasing Ω. History offers a mixed message about the capacity of humans to innovate and act in time to avoid collapse. At local and regional scales, many multiple past civilizations (e.g., Greece, Rome, Angkor Wat, Teotihuacan) failed to adapt to changing social and ecological conditions and crashed catastrophically. At the same time, human ingenuity and technological innovations allowed the global population and economy to grow at near-exponential rates. This growth has been fueled by exploiting new energy sources, transitioning among animal, hydro, wind, wood, coal, oil, natural gas, nuclear, photovoltaic solar, geothermal, and others. The implications of past localized collapses and global growth are of questionable relevance to the current situation, however, because now, for the first time in history, humanity is facing a global chemical energy limit. The earth-space battery paradigm provides a simple framework for understanding the historical effects of humans on the energy dynamics of the biosphere, including the unalterable thermodynamic boundaries that now pose severe challenges to the future of humankind. Living biomass is the energy capital that runs the biosphere and supports the human population and economy. There is an urgent need not only to halt the depletion of this biological capital, but to move as rapidly as possible toward an approximate equilibrium between NPP and respiration. There is simply no reserve tank of biomass for planet Earth. The laws of thermodynamics have no mercy. Equilibrium is inhospitable, sterile, and final.

Materials and Methods

To calculate omega in Fig. 5, we used the data on increase in population *N* from the years 0 to 1950 and from 1950 to 2000 from the US Census Bureau (36, 37). In all cases, if there was a variation in population estimates for a given year, to be conservative, we used the lowest. Phytomass energy content *P* required a continuous function to represent all years from 0 to 2000. We used second-order equations to fit the data points in Fig. 3. The first three data points (years 0–1800) were represented by phytomass energy = $[35 - 1.70 \times 10^{-6}\ (\text{year})^2 - 1.801 \times 10^{-3}\ (\text{year}) - 1.8031 \times 10^{-3}]$ zeta joules. The remaining data points (years 1800–2000) were represented by phytomass energy = $[35 - 3.386 \times 10^{-5}\ (\text{year})^2 + 9.373^{-2}\ (\text{year}) - 67.770]$ zeta joules.

ACKNOWLEDGMENTS. The University of Georgia's Environmental Engineering students are gratefully acknowledged for persistent engaging questions and deep discussions that enhanced key points in this research. This work was funded in part by National Science Foundation Macrosystems Biology Grant EF 1065836 (to J.H.B.).

1 Brown JH, et al. (2004) Toward a metabolic theory of ecology. *Ecology* 85(7):1771–1789.
2 Sibly RM, Brown JH, Kodric-Brown A (2012) *Metabolic Ecology, A Scaling Approach* (John Wiley & Sons, Ltd, West Sussex, UK).
3 Payne JL, et al. (2011) The evolutionary consequences of oxygenic photosynthesis: A body size perspective. *Photosynthesis Res* 107(1):37–57.
4 Hall CAS, Klitgaard KA (2012) *Energy and the Wealth of Nations: Understanding the Biophysical Economy* (Springer, New York).
5 Woodwell GM, et al. (1978) The biota and the world carbon budget. *Science* 199(4325):141–146.
6 Whittaker RH (1970) *Communities and Ecosystems* (Macmilliam, New York).
7 Hall CAS, Day JW (2009) Revisiting the limits to growth after peak oil. *Am Sci* 97(3):230–237.
8 Brown JH, et al. (2011) Energetic limits to economic growth. *Bioscience* 61(1):19–26.
9 Schneider ED, Kay JJ (1994) Life as a manifestation of the second law of thermodynamics. *Math Comput Model* 19(6-8): 25–48.
10 Bazilevich NI, Rodin LY, Rozov NN (1971) Geographical aspects of biological productivity. *Sov Geogr* 12(5):293–317.
11 Smil V (2011) Harvesting the biosphere: The human impact. *Popul Dev Rev* 37(4):613–636.
12 Smil V (2013) *Harvesting the Biosphere: What We Have Taken from Nature* (MIT Press, Cambridge, MA).
13 Houghton RA (2010) How well do we know the flux of CO2 from land-use change? *Tellus, Series B* 62(5):337–351.
14 Houghton RA, Hall F, Goetz SJ (2009) Importance of biomass in the global carbon cycle. *J Geophys Res* 114(G2): G00E03.
15 Jevons WS (1866) *The Coal Question* (Macmillan and Company, London), 2nd Ed.
16 BP (2013) Statistical review of world energy. Available at www.bp.com/content/dam/bp/pdf/statistical-review/statistical_review_of_world_energy_2013.pdf. Accessed June 26, 2015.
17 Brown JH, et al. (2014) Macroecoloty meets macroeconomics: Resource scarcity and global sustainablity. *Ecol Eng* 65:24–32.
18 Vitousek PM, et al. (1997) Human alteration of the global nitrogen cycle. *Ecological Applications* 7(3):737–750.
19 Postel SL, Daily GC, Ehrlich PT (1996) Human appropriation of renewable fresh water. *Science* 271(5250):785–788.
20 Nilsson C, Reidy CA, Dynesius M, Revenga C (2005) Fragmentation and flow regulation of the world's large river systems. *Science* 308(5720):405–408.
21 Hooke RL, Martin-Duque JF, Pedraza J (2012) Land transformation by humans: A review. *GSA Today* 22(12):4–10.
22 Pimm SL, Russell GJ, Gittleman JL, Brooks TM (1995) The future of biodiversity. *Science* 269(5222):347–350.
23 Felix E, Dubois O (2012) *Energy-Smart Food at FAO* (Food and Agriculture Organization of the United Nations, Rome).
24 Canning C, et al. (2010) *Energy Use in the U.S. Food System* (USDA, Washington, DC).
25 Schramski JR, et al. (2013) Energy as a potential systems-level indicator of sustainability in organic agriculture: Case study model of a diversified, organic vegetable production system. *Ecol Modell* 267:102–114.
26 Pheiffer DA (2006) *Eating Fossil Fuels: Oil, Food, and the Coming Crisis in Agriculture* (New Society Publishers, Gabriola Island, BC, Canada).
27 Pimentel D, Pimentel M (2008) *Food, Energy, and Society* (CRC Press, Boca Raton, FL).
28 Bai ZG, et al. (2008) Proxy global assessment of land degradation. *Soil Use Manage* 24(3):223–234.
29 Sanderson EW, et al. (2002) The human footprint and the last of the wild. *Bioscience* 52(10):891–904.
30 Ehrlich PR, Kareiva PM, Daily GC (2012) Securing natural capital and expanding equity to rescale civilization. *Nature* 486(7401):68–73.
31 Barnosky AD, et al. (2012) Approaching a state shift in Earth's biosphere. *Nature* 486(7401):52–58.
32 Jacobson MZ, Delucchi MA (2011) Providing all global energy with wind, water, and solar power, Part I: Technologies, energy resources, quantities and areas of infrastructure, and materials. *Energy Policy* 39(3):1154–1169.
33 IPCC (2011) *Special Report on Renewable Energy Sources and Climate Change Mitigation* (Cambridge Univ Press, Cambridge, UK).
34 Palmer G (2014) *Energy in Australia: Peak Oil, Solar Power, and Asia's Economic Growth*, 1st Ed (Springer International Publishing, Cham, Switzerland).
35 Prieto PA, Hall CAS (2013) *Spain's Photovoltaic Revolution* (Springer, New York).
36 US Census Bureau (2013) Historical estimates of world population. Available at https://www.census.gov/population/international/data/worldpop/table_history.php. Accessed June 26, 2015.
37 US Census Bureau (2013) Total midyear population for the world: 1950-2050. Available at https://www.census.gov/population/international/data/idb/worldpoptotal.php. Accessed June 26, 2015.
38 Smil V (2008) *Energy in Nature and Society: General Energetics of Complex Systems* (MIT Press, Cambridge, MA).
39 Numerical Terradynamic Simulation Group (2004) Four years of MOD17 annual NPP. Available at images.ntsg.umt.edu/. Accessed June 26, 2015.