Energetic Limits to Economic Growth

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The human population and economy have grown exponentially and now have impacts on climate, ecosystem processes, and biodiversity far exceeding those of any other species. Like all organisms, humans are subject to natural laws and are limited by energy and other resources. In this article, we use a macroecological approach to integrate perspectives of physics, ecology, and economics with an analysis of extensive global data to show how energy imposes fundamental constraints on economic growth and development. We demonstrate a positive scaling relationship between per capita energy use and per capita gross domestic product (GDP) both across nations and within nations over time. Other indicators of socioeconomic status and ecological impact are correlated with energy use and GDP. We estimate global energy consumption for alternative future scenarios of population growth and standards of living. Large amounts of energy will be required to fuel economic growth, increase standards of living, and lift developing nations out of poverty.

Keywords: energy, economic growth, economy, human macroecology, scaling

The human species has an interesting duality. On the one hand, *Homo sapiens* is just another species, subject to the same scientific laws as the millions of other animals, plants, and microbes. On the other hand, humans are unique. No other species in the history of Earth has achieved such ecological dominance and created such complex socioeconomic systems. Because of this duality, humans have been studied by both natural and social scientists, but often from very different perspectives (Arrow et al. 2004).

In just a few thousand years the human population has colonized the entire world and grown to almost 7 billion. Humans now appropriate 20% to 40% of terrestrial annual net primary production, and have transformed the atmosphere, water, land, and biodiversity of the planet (Vitousek et al. 1997, Haberl et al. 2007). For centuries some have questioned how long a finite planet can continue to support near-exponential population and economic growth (e.g., Malthus 1798, Ehrlich 1968, Meadows et al. 1972). Recent issues such as climate change, the global decline in population growth rate, the depletion of petroleum reserves and resulting increase in oil prices, and the recent economic downturn have prompted renewed concerns about whether longstanding trajectories of population and economic growth can continue (e.g., Arrow et al. 2004). These serious issues fall within the purview of both the natural and social sciences—especially ecology and economics.

This article integrates perspectives from physics, ecology, and economics with an analysis of extensive global data to show how scientific laws governing the flows of energy in the biosphere affect socioeconomic activity. Our purpose is neither to pit ecology against economics nor to predict future population and economic trends; rather, we use theoretical perspectives from thermodynamics, allometry, and

metabolic ecology (McMahon and Bonner 1983, Schneider and Kay 1995, Brown et al. 2004) and empirical approaches from macroecology (Brown 1995) to document energetic constraints on human ecology that have important implications for modern humans.

The central role of energy

Economic growth and development require that energy and other resources be extracted from the environment to manufacture goods, provide services, and create capital. The central role of energy is substantiated by both theory and data.

Key theoretical underpinnings come from the laws of thermodynamics: first, that energy can be neither created nor destroyed, and second, that some capacity to perform useful work is lost as heat when energy is converted from one form to another. Complex, highly organized systems, including human economies, are maintained in states far from thermodynamic equilibrium by the continual intake and transformation of energy (Soddy 1926, Odum 1971, Georgescu-Roegen 1977, Ruth 1993, Schneider and Kay 1995, Hall et al. 2001, Chen 2005, Smil 2008).

Empirically, the central role of energy in modern human economies is demonstrated by the positive relationship between energy use and economic growth (Shafiee and Topal 2008, Smil 2008, Payne 2010). Here, we take a macroecological perspective and quantify statistical relationships between energy use and economic activity for 220 nations over 24 years, using data from the International Energy Agency (IEA; *www.iea.org/stats/index.asp*) and World Resources Institute (WRI; *http://earthtrends.wri.org/index.php*). Per capita energy consumption for each country is calculated as the sum of human biological metabolism plus the energy obtained from

all other sources. Individual biological metabolism was estimated from data on daily caloric intake for each country and converted to watts per individual. Energy use from all other sources, including fossil fuels and renewable energy supplies, was obtained from the IEA. For our measure of economic activity, we used the WRI's data for gross domestic product (GDP), the market value of all goods and services produced within a country per year (Mankiw 2006). Both energy use and GDP are expressed on a per capita basis. So, per capita GDP can be thought of as an index of an average individual's share of his or her country's economy, and per capita energy use as the power required to sustain that level of economic activity.

Figure 1 shows the relationship between energy use and GDP plotted on logarithmic axes, with each colored line indicating the trajectory for a single country over the period 1980–2003. A regression through the mean GDP, G for mean energy consumption and E for each country over the 24-year period, accounts for 76% of the variation. The fitted regression describes the scaling of per capita energy use with per capita GDP as a power law: $E = 4.13G^{0.76}$ (figure 1; see also figure S1c in supplemental online materials at *http://caliber. ucpress.net/doi/suppl/10.1525/ bio.2011.61.1.7*). The sublinear slope, 0.76, indicates that the rate of per capita energy consumption associated with greater economic activity increases less rapidly than GDP itself. Countries with larger economies take advantage of economies of scale and new technologies to use energy more efficiently on a per capita basis (Hoffert et al. 1998). For example, there is both a positive relationship and an economy of scale between economic growth and the amount of infrastructure, such as roads, pipelines, and power lines, that distributes energy resources (Easterly and Rebelo 1993). The relationship between energy use and GDP holds across countries spanning the entire range of economic development from poor-

est to richest, encompassing two orders of magnitude in both energy use (100 to 10,000 watts) and wealth ($500 to $50,000).

A similar trend occurs within countries over time. The vast majority of nations we analyzed (74%) increased both energy use and GDP from 1980 to 2003 and exhibited positive correlations across the 24 years (mean slope = 0.59; 95% confidence interval = 0.45–0.72; figure 2; see also figure S1 at *http://caliber.ucpress.net/doi/suppl/10.1525/bio.2011.61.1.7*). Countries notable for sustained recent development, such as
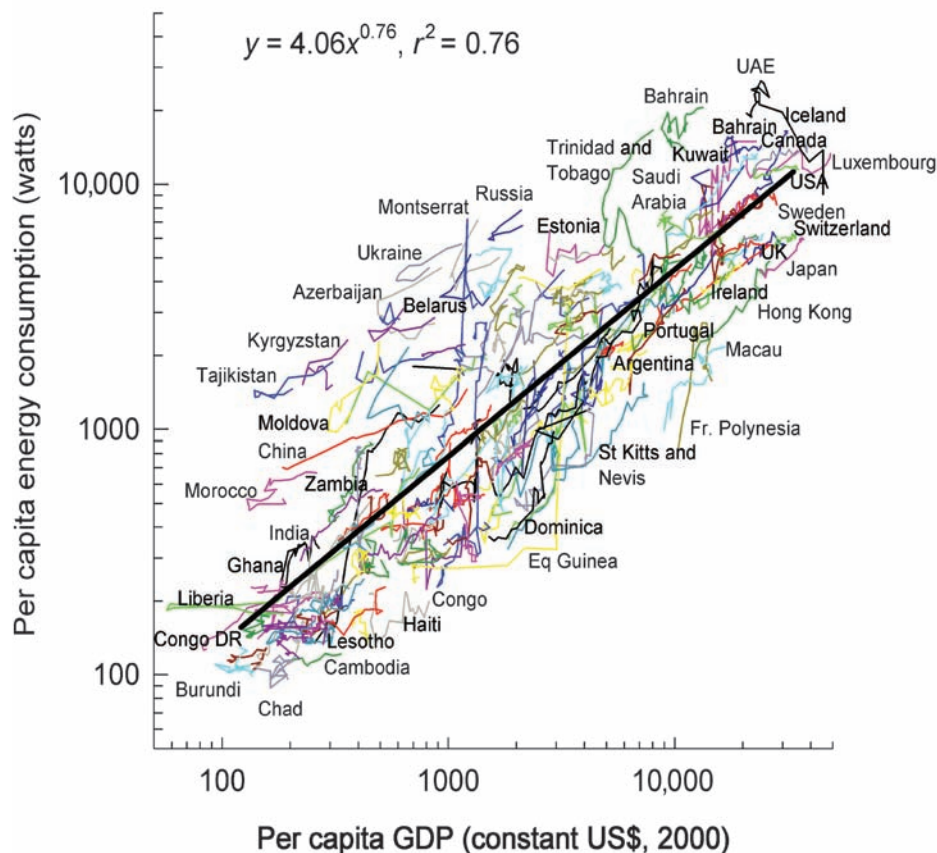

Figure 1. The relationship between per capita energy use and per capita gross domestic product (GDP; in US dollars) of countries, plotted on logarithmic axes, from 1980 to 2003. Note that the slope or exponent, 0.76 (95% confidence interval: 0.69–0.82), is close to three-quarters, which is the canonical value of the exponent for the scaling of metabolic rate with body mass in animals. If per capita GDP is taken as the size of an average individual's economy and per capita energy use as the rate of energy consumption required to support that economy, this relationship may not be coincidental. Total per capita energy consumption is calculated as the caloric intake of humans (about 130 watts) plus the energy derived from all other sources, including fossil fuels and renewables. The thin colored lines show trends for individual countries from 1980 to 2003. The thick black line is a regression model fit to the mean values for each nation during this period. GDP data are from the World Resources Institute (http://earthtrends.wri.org/index.php). Total energy consumption data are calculated from the sum of energy consumption from eating (data from the World Resources Institute) plus all other sources of energy consumed for other purposes such as utilities, manufacturing, and transportation. Source: Data are from the International Energy Agency at www.iea.org/stats/index.asp.

China and India, show trajectories of continually increasing energy use. The patterns in figures 1 and 2 are consistent with the increasing energy use that fueled socioeconomic development throughout history (Tainter 1988, Smil 2008). For example, from 1850 to 2000, while the global human population grew fivefold, world energy use increased 20-fold and fossil fuel use rose more than 150-fold (Holdren 2008).

The relationship between energy use and GDP depicted in figure 1 raises several important issues. One is the considerable variation around the regression line: Countries with similar per capita GDPs differ by more than an order of magnitude in per capita energy consumption. We did not analyze this residual variation quantitatively, although it would be illuminating to do so. For example, several oil-exporting nations (e.g., the United Arab Emirates, Bahrain, Tajikistan, and Azerbaijan) are consistent outliers, with high values of energy use relative to GDP. We hypothesize that much of this energy is used to extract oil that is then exported to and consumed by industrialized nations. Although the United States is among the countries with highest per capita energy use, several other developed countries have comparably high values. We hypothesize that in some of them, such as Iceland, Sweden, and Norway, large quantities of energy are used to heat houses and workplaces during cold winters at high latitudes.

Additionally, some of the variation in figure 1 may reflect error or a lack of standardization in the ways different coun-
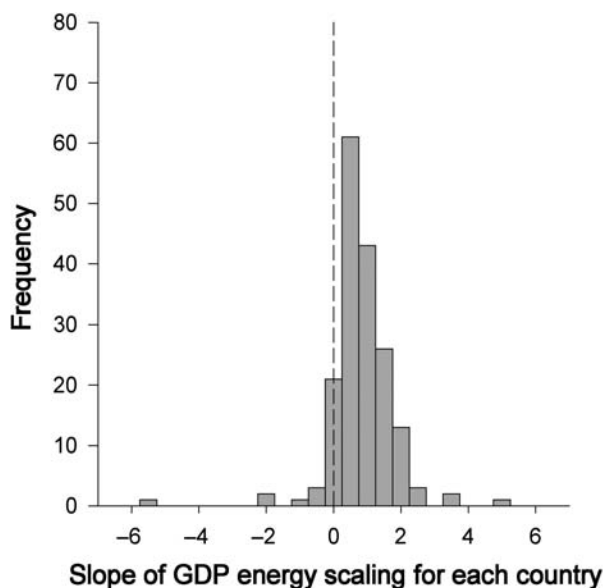

*Figure 2. The frequency distribution of exponents (slopes from log-log plots) of economic trajectories of per capita energy use as a function of per capita gross domestic product (GDP) within countries over the time series from 1980 to 2003. The average slope is approximately 0.6 and nearly all countries showed positive growth over the 24-year period. Source: Data are from the World Resources Institute (*http://earthtrends.wri.org/index.php*) and the International Energy Agency (*www.iea.org/stats/index.asp*).*

tries have calculated energy use and GDP. The data sources that we used (IEA and WRI), although probably the best available, have their limitations. The original data are self-reported by the countries, and some of the abrupt, seemingly inexplicable changes in the trajectories in figure 1 may simply reflect errors or changing methods of estimating energy use, GDP, or both. One strength of our macroecological approach (Brown 1995), however, is that the hundreds of data points distributed over orders of magnitude variation mean that modest errors and other sources of uncontrolled noise in the data do not obscure the strong signals that are manifest in the robust patterns within and across countries over time.

Another question is, what are the independent and dependent variables? Does energy use support economic development or does economic development drive energy consumption? Financial and energy economists have used econometric techniques to analyze time series of energy consumption and economic growth within countries in an effort to assess causal relationships, but they have reached no clear consensus about whether energy use causes economic growth, or vice versa (see Mahadevan and Asafu-Adjaye 2007, Payne 2010). By analogy to biological allometry, we plotted per capita energy use as the dependent variable and per capita GDP as the independent variable; this is analogous to plotting the rate of energy use of an animal as a function of its body size. The exponent for the scaling of energy use as a function of GDP, 0.76, is reminiscent of the three-quarter-power scaling of metabolic rate with body mass in animals (Kleiber 1961, McMahon and Bonner 1983). This may not be coincidental. In a very real sense both animals and economies have "metabolisms." Both consume, transform, and allocate energy to maintain complex adaptive systems far from thermodynamic equilibrium. The energy and other resources that sustain these systems are supplied by hierarchically branching networks, such as the blood vessels and lungs of mammals and the oil pipelines, power grids, and transportation networks of nations. Models of these networks suggest that three-quarter-power scaling optimizes distribution of resources (West et al. 1997, Banavar et al. 2010).

Some may be concerned that the relationships in figures 1 and 2 are "just correlations" that do not necessarily imply any underlying mechanism or causality. We disagree. All science is ultimately based on correlations—between dependent and independent variables, model predictions and empirical measurements, or experimental treatments and controls. Any mechanism or causation comes from logical inference. We infer that energy limits economic activity through direct causal mechanisms. The evidence for this inference is presented above and comes from three sources: (1) theory, the application of the second law of thermodynamics to complex adaptive systems; (2) data, the robust relationship between per capita energy use and per capita GDP across both space (the 220 nations of the world) and time (24 years); and (3) analogy, the similarity

between biological and socioeconomic metabolism. We find the last to be especially compelling. Just as a body has a metabolism that burns food energy to survive and grow, a city or national economy has a metabolism that must burn fuel in order to sustain itself and grow. Just as higher metabolic rates are required to sustain and grow larger, more complex bodies (Kleiber 1961, McMahon and Bonner 1983), so higher rates of energy consumption are required to sustain and grow larger, more developed economies that provide greater levels of technological development and higher standards of living.

Quantitative relationships among energy use, GDP, and other socioeconomic indicators

Some may be concerned that the relationships in figures 1 and 2 do not reflect what is "really important," which might be some aspect of quality of life rather than GDP. However, nearly all measures of economic activity and standard of living are closely correlated with both GDP and energy use (figure 3; for additional variables, see figure S2 in the supplemental online materials at *http://caliber.ucpress.net/ doi/suppl/10.1525/bio.2011.61.1.7*). These include measures of nutrition, education, health care, resource use, technology, and innovation. These relationships are not surprising and reflect mechanistic underpinnings. It takes money and energy to train engineers, MDs, and PhDs; to produce vaccines, drugs, and medical equipment; and to construct and maintain road, rail, airplane, cell phone, and Internet networks, hospitals and research centers, parks and conservation areas, and modern buildings and cities. The ecological footprint, an aggregate measure of per capita resource consumption and waste production, also increases with energy use and GDP (figure 3; Dietz et al. 2007). Figure 3 shows that it has not been possible to increase socially desirable goods and services substantially without concomitantly increasing the consumption of energy and other natural resources and without increasing environmental impacts that now include climate change, pollution, altered biogeochemical cycles, and reduced biodiversity.

Energetic implications for future economic growth

These empirical patterns, together with their theoretical underpinnings, raise the question of whether economic growth and associated increases in human population, resource use, technological development, and standard of living can continue their present trajectories (Grossman and Krueger 1995, Ausubel 1996). In figure 4 we develop some quantitative scenarios. We caution that these are not intended to be predictions of the future; rather, they are extrapolations of the power-law relationship shown in figure 1 to estimate the quantity of energy that would be required to support different global populations and levels of economic development. So, for example, raising the current global population to the standard of living in the United States would require a nearly fivefold increase in the rate of energy consumption, from 17 to 77 terawatts

(1 terawatt = 10^{12} watts). Population growth must also be considered in any future scenario. To support a projected global population of 9.5 billion in 2050 with an average standard of living equivalent to the current US lifestyle would require about 268 terawatts, 16 times the current global energy use. Even maintaining this increased population at the more modest Chinese standard of living would require 2.5 times more energy than is used today (figure 4).

There are good reasons, however, such simple scenarios based on extrapolations of current population and economic trends may be imprecise. Our calculations incorporate the economy of scale implicit in the nonlinear scaling of energy use with GDP, but do not take into account many potentially important factors, such as greater efficiency that may be triggered by energy shortages; technological innovations that may increase energy supplies; and socioeconomic, demographic, and behavioral changes. Indeed, the global human socioeconomic system is complex, poised far from thermodynamic equilibrium by high rates of energy input and transformation. Such systems have unpredictable nonlinear dynamics, making it nearly impossible to predict very far into the future (Schneider and Kay 1995).

One thing is clear: If the relationships depicted in figures 1–3 characterize fundamental causal relationships among the rate of energy use, level of economic activity, and standard of living, then additional economic growth and development will require some combination of (a) increased energy supply, (b) decreased per capita energy use, and (c) decreased human population. We consider each in turn.

Increased energy supply. The sources of energy that may be used to support future economic growth include finite stocks of fossil fuels as well as nuclear, renewable, and other proposed but unproven technologies. Fossil fuels currently provide 85% of humankind's energy needs (figure 5), but they are effectively fixed stores that are being depleted rapidly (Heinberg 2003, IEA 2008, Hall and Day 2009). Conventional nuclear energy currently supplies only about 6% of global energy; fuel supplies are also finite, and future developments are plagued by concerns about safety, waste storage, and disposal (Nel and Cooper 2009). A breakthrough in nuclear fusion, which has remained elusive for the last 50 years, could potentially generate enormous quantities of energy, but would likely produce large and unpredictable socioeconomic and environmental consequences. Solar, hydro, wind, and tidal renewable energy sources are abundant, but environmental impacts and the time, resources, and expenses required to capture their energy limit their potential (Hall and Day 2009). Biofuels may be renewable, but ecological constraints and environmental impacts constrain their contribution (Fargione et al. 2008). More generally, most efforts to develop new sources of energy face economic problems of diminishing returns on energy and monetary investment (Hall et al. 1986, Tainter 1988, Allen et al. 2001, Tainter et al. 2003).
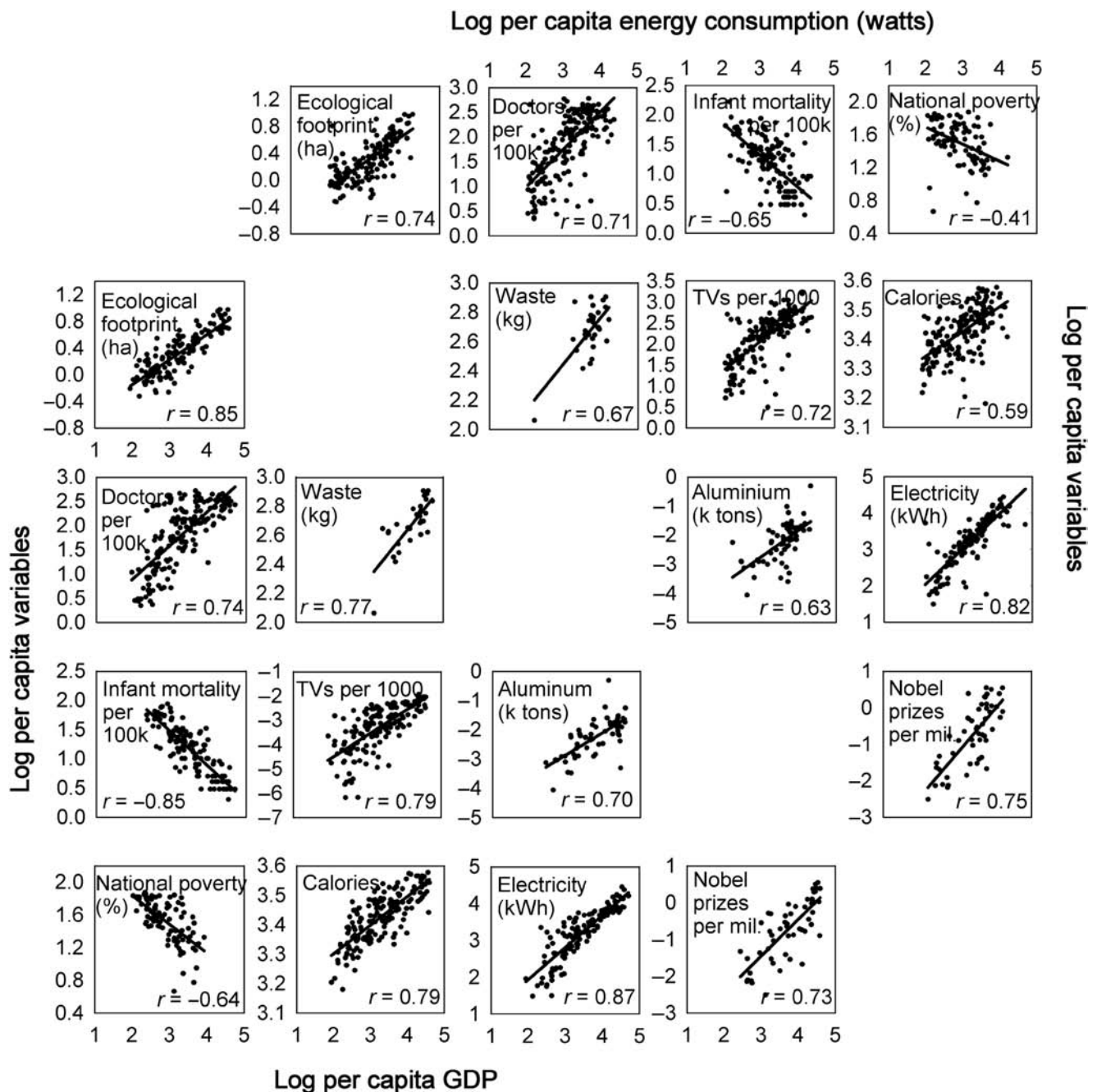
Figure 3. Variables reflecting socioeconomic status and standard of living are strongly correlated with per capita energy use (upper panels) and per capita gross domestic product (GDP; lower panels). The variables include measures of health and wellness (population growth rate, doctors per 100,000 people, life expectancy, infant mortality, caloric intake, national poverty), energy use (electricity [kilowatt hours], residential energy [kilograms of oil equivalent]), resource consumption (meat, televisions, aluminum [kilotons], waste [kilograms]), intellectual and technological contributions (Nobel Prizes, patents), and ecological impacts (ecological footprint [in hectares]). All correlations (r) are significant (P < 0.05). Data sources are provided in supplemental online materials.

Decreased per capita energy use. The Malthusian-Darwinian dynamic that has shaped the evolution of human behavior and demography has created powerful tendencies for individuals and societies to exploit all available resources and use all available technologies to enhance personal status, biological fitness, and societal wealth (Lotka 1922). Poor people migrate to cities and to other countries to improve their prospects. Citizens of developing countries such as China and India are not usually satisfied with the status quo, and understandably want to live like those in the de-
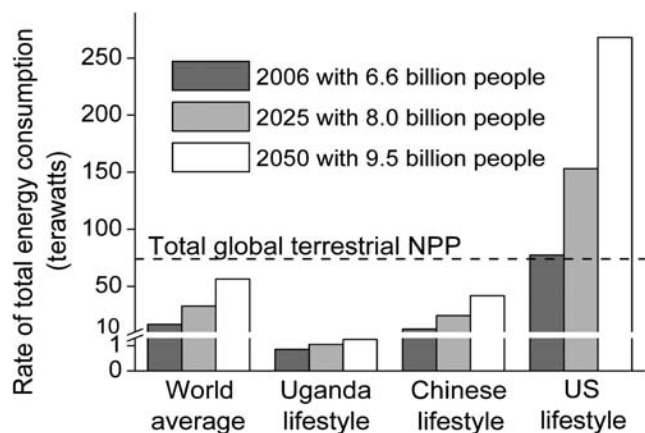
Figure 4. Current and projected global energy consumption based on alternative scenarios of population growth (2006, 2025, and 2050) and standard of living (equivalent to contemporary Uganda, China, and United States). Dashed line is total global terrestrial net primary productivity (NPP), 75 terawatts (Haberl et al. 2007). Data sources and calculation methods can be found in supplemental online materials.
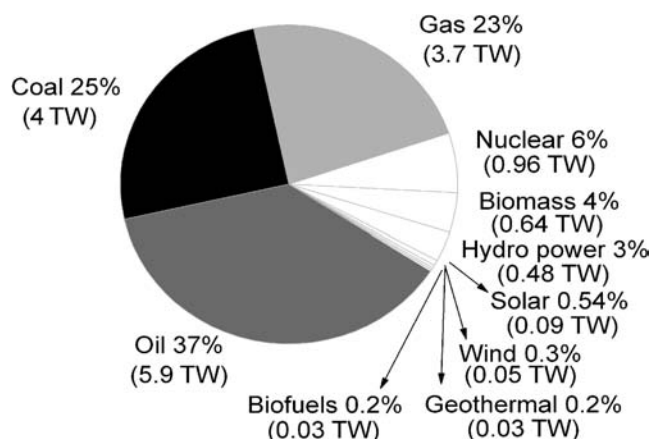

Figure 5. Sources of energy currently consumed by the global human economy. Total annual consumption is approximately 15.9 terawatts (TW, 1 terawatt = 10^{12} watts), of which about 85% comes from fossil fuels, 6% from nuclear energy, and the remaining 9% from solar, hydro, wind, and other renewable sources (BP 2009, REN21 2009).

veloped world. People in the richest nations are reluctant to sacrifice economic growth—much less give up their automobiles, electronics, and organ transplants—so that people in poorer countries can have bicycles, personal computers, and flu shots.

Decreased human population. With growing standards of living and rates of energy use, parents tend to invest more resources in fewer children (Moses and Brown 2003). This trade-off between the number and quality of offspring contributes to demographic transitions, where family size and the rate of population growth decrease with increasing economic development (Thompson 1929). The global population growth rate has declined in the last decade, but only a few developed countries currently have zero or negative population growth (WRI, *http://earthtrends.wri.org/index.php*). The relationship between family size and per capita energy use suggests that five times the current rates of energy supply will be required to achieve a global level of socioeconomic development capable of stabilizing the human population without infringing on the freedom of individuals to have as many children as they choose (Moses and Brown 2003, DeLong et al. 2010).

The bottom line is that an enormous increase in energy supply will be required to meet the demands of projected population growth and lift the developing world out of poverty without jeopardizing current standards of living in the most developed countries. And the possibilities for substantially increasing energy supplies are highly uncertain. Moreover, the nonlinear, complex nature of the global economy raises the possibility that energy shortages might trigger massive socioeconomic disruption. Again, consider the analogy to biological metabolism: Gradually reducing an individual's food supply leads initially to physiological adjustments, but then to death from starvation, well before all food supplies have been exhausted.

Mainstream economists historically have dismissed warnings that resource shortages might permanently limit economic growth. Many believe that the capacity for technological innovation to meet the demand for resources is as much a law of human nature as the Malthusian-Darwinian dynamic that creates the demand (Barro and Sala-i-Martin 2003, Durlauf et al. 2005, Mankiw 2006). However, there is no scientific support for this proposition; it is either an article of faith or based on statistically flawed extrapolations of historical trends. The ruins of Mohenjo Daro, Mesopotamia, Egypt, Rome, the Maya, Angkor, Easter Island, and many other complex civilizations provide incontrovertible evidence that innovation does not always prevent socioeconomic collapse (Tainter 1988, Diamond 2004).

Conclusions

We are by no means the first to write about the limits to economic growth and the fundamental energetic constraints that stem directly from the laws of thermodynamics and the principles of ecology. Beginning with Malthus (1798), both ecologists and economists have called attention to the essential dependence of economies on natural resources and have pointed out that near-exponential growth of the human population and economy cannot be sustained indefinitely in a world of finite resources (e.g., Soddy 1922, Odum 1971, Daly 1977, Georgescu-Roegen 1977, Cleveland et al. 1984, Costanza and Daly 1992, Hall et al. 2001, Arrow et al. 2004, Stern 2004, Nel and van Zyl 2010). Some ecological economists and systems ecologists have made

similar theoretical arguments for energetic constraints on economic systems (e.g., Odum 1971, Hall et al. 1986). However, these perspectives have not been incorporated into mainstream economic theory, practice, or pedagogy (e.g., Barro and Sala-i-Martin 2003, Mankiw 2006), and they have been downplayed in consensus statements by influential ecologists (e.g., Lubchenco et al. 1991, Palmer et al. 2004, ESA 2009) and sustainability scientists (e.g., NRC 1999, Kates et al. 2001, ICS 2002, Kates and Parris 2003, Parris and Kates 2003, Clark 2007).

Our explicitly macroecological and metabolic approach uses new data and analyses to provide quantitative, mechanistic, and practically relevant insights into energetic limits on economic growth. We hope the evidence and interpretations presented here will call the attention of scientists, policymakers, world leaders, and the public to the central but largely underappreciated role of energetic limits to economic growth.

Acknowledgments

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