Ecological Engineering 65 (2014) 24–32

Contents lists available at ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng

Macroecology meets macroeconomics: Resource scarcity and global sustainability

James H. Brown[a,b,*], Joseph R. Burger[a], William R. Burnside[c], Michael Chang[a], Ana D. Davidson[d], Trevor S. Fristoe[a], Marcus J. Hamilton[b], Sean T. Hammond[a], Astrid Kodric-Brown[a], Norman Mercado-Silva[a,e], Jeffrey C. Nekola[a], Jordan G. Okie[f]

[a] Department of Biology, University of New Mexico, Albuquerque, NM 87131, United States
[b] Santa Fe Institute, Santa Fe, NM, United States
[c] National Socio-Environmental Synthesis Center, Annapolis, MD, United States
[d] Department of Ecology & Evolution, Stony Brook University, Stony Brook, NY, United States
[e] School of Natural Resources and the Environment, University of Arizona, Tucson, AZ, United States
[f] School of Earth and Space Exploration, Arizona State University, Tempe, AZ, United States

ARTICLE INFO

Article history:
Received 29 November 2012
Received in revised form 17 July 2013
Accepted 18 July 2013
Available online 27 August 2013

Keywords:
Ecological economics
Economic growth
Human ecology
Macroecology
Resource scarcity
Global sustainability

ABSTRACT

The current economic paradigm, which is based on increasing human population, economic development, and standard of living, is no longer compatible with the biophysical limits of the finite Earth. Failure to recover from the economic crash of 2008 is not due just to inadequate fiscal and monetary policies. The continuing global crisis is also due to scarcity of critical resources. Our macroecological studies highlight the role in the economy of energy and natural resources: oil, gas, water, arable land, metals, rare earths, fertilizers, fisheries, and wood. As the modern industrial-technological-informational economy expanded in recent decades, it grew by consuming the Earth's natural resources at unsustainable rates. Correlations between per capita GDP and per capita consumption of energy and other resources across nations and over time demonstrate how economic growth and development depend on "nature's capital". Decades-long trends of decreasing per capita consumption of multiple important commodities indicate that overexploitation has created an unsustainable bubble of population and economy.

1. Introduction

The greatest challenge of the 21st Century is to secure a sustainable future for humanity. Our informal Human Macroecology Group at the University of New Mexico is one of several collaborative groups investigating the biophysical capacity of the Earth to support human populations and economies. Our approach is "macroecological". By "macro" we mean that our research, based mostly on statistical analysis of large datasets, considers a wide range of spatial and temporal scales, from local to global and from years to millennia. By "ecological" we indicate that our focus is on human-environment relationships, especially the flows of energy, materials, and information which obey well-established physical laws and biological principles, but have uniquely human features. Our guiding principle is that there is much to be learned by studying humans from an explicitly ecological perspective – a perspective that should be complementary to, but is largely missing from the social sciences and from socioeconomic policy (Burnside et al., 2011).

Much of our work has focused on dependence on resources for population growth and economic development (Brown et al., 2011; Burger et al., 2012; Nekola et al., 2013). The results of our analyses provide a sobering perspective on the current economic situation – and one that contrasts with that of most economists. The global recession of 2008 was the deepest and most long-lasting since the Great Depression. It is not over yet. To recover completely and prevent an even greater crash, most economists and policymakers are calling for economic growth. The implication is that if we can just get the right monetary, fiscal, and social policies implemented, then unemployment and deficits will go down, housing and industry will rebound, and the economy will start growing again at a healthy pace. This perspective comes from considering only the internal workings of the economy. But why is the recession global? Why is it so severe and long-lasting? Why is the

* Corresponding author at: Department of Biology, University of New Mexico, Albuquerque, NM 87131, United States. Tel.: +1 505 277 9337; fax: +1 505 277 0304.
E-mail address: jhbrown@unm.edu (J.H. Brown).

0925-8574/$ – see front matter
http://dx.doi.org/10.1016/j.ecoleng.2013.07.071

prescribed economic growth so hard to achieve? These are not just matters of jobs and deficits. The fundamental underlying cause of the decades-long economic trends that culminated in the current recession is depletion of global natural resources. Economic growth and development depend on more than moving money, people, and information; on more than capital and labor, principal and interest, credit and debt, taxation and investment. They also depend on "nature's capital" (e.g., Costanza et al., 1997; Daily, 1997). Economies extract energy and material resources from the Earth and transform them to produce goods and services. In the last few decades critical resources have been overexploited (Goodland, 1995; Wackernagel and Rees, 1998; Rockström et al., 2009; Bardi, 2011; Burger et al., 2012; The Royal Society, 2012; Wijkman and Rockström, 2013).

2. Background

The human population has grown near-exponentially for about 50,000 years. *Homo sapiens* has expanded out of Africa to colonize the entire world and become the most dominant species in the history of the Earth. Our species has transformed the land, water, atmosphere, and biodiversity of the planet. This growth is a consequence of what we call the Malthusian-Darwinian Dynamic (Nekola et al., 2013). It represents the uniquely human expression of the universal biological heritage that we share with all living things. It has two parts: the Malthusian part, after Thomas Malthus, is the tendency of a population to increase exponentially until checked by environmental limits; the Darwinian part, after Charles Darwin, is the tendency of a population to adapt to the environment in order to push back the limits and keep growing. A special feature of humans is the central role of cultural evolution, which has resulted in rapid changes in behavior, social organization, and resource use.

The expansion of the human population has been accompanied by economic growth and development, and facilitated by technological innovations. The human economy has expanded from the hunting-gathering-bartering economies of subsistence societies to the industrial-technological-informational economies of contemporary civilization. Advances in agriculture used water, fertilizers, new varieties of plants, and animal and mechanical labor to grow food and fiber. Innovations in fisheries supplied additional, protein-rich food. New technologies used wood, bricks, cement, metals, and glass to construct living and working places. Newly developed vaccines and drugs kept parasites and diseases at bay. Energy from burning wood and dung, and subsequently coal, oil, and gas, supplemented with nuclear, solar, wind, and other sources, fueled the development of increasingly complex societies, culminating in our current interconnected civilization with its enormous infrastructure and globalized economy.

How long can recent demographic population and economic trends continue? For more than 200 years, "Malthusians" (e.g., Malthus, 1798; Ehrlich, 1968; Meadows et al., 1972) have argued that the human population cannot continue its near-exponential growth because essential resources supplied by the finite Earth will ultimately become limiting. This perspective has been countered by "Cornucopians" who have argued that there is no hard limit to human population size and economic activity, because human ingenuity and technological innovation provide an effectively infinite capacity to increase resource supply (e.g., Simon, 1981; Barro and Sala-i-Martin, 2003; Mankiw, 2008). So far, both the Malthusians and Cornucopians can claim to be right. Earlier civilizations have grown, flourished, and crashed, but these were always local or regional events (Tainter, 1988; Diamond, 2006). Innovations in agriculture, industry, medicine, and information technology allowed the global population and its economy to grow (Dilworth, 2010).

Now, however, there is increasing concern that modern humans have depleted the Earth's energy and material resources to the point where continued population and economic growth cannot be sustained on a global scale (Arrow et al., 1995, 2004; Goodland, 1995; Wackernagel and Rees, 1998; Rockström et al., 2009; Burger et al., 2012; Hengeveld, 2012; Klare, 2012; Mace, 2012; Moyo, 2012; The Royal Society, 2012; Ehrlich and Ehrlich, 2013; Wijkman and Rockström, 2013).

3. Energy

The most critical resource is energy. The development of the modern global industrial-technological-informational economy has been fueled by ever-increasing rates of energy consumption, mostly from fossil fuels. The dependence of economic growth and development on energy is incontrovertible. Much evidence for this is given in papers in this Special Issue by Day et al. (2014) and Hall and Day (2014) (this issue), and in other publications by these and other authors (e.g., Odum, 1971; Smil, 2008; Day et al., 2009; Hall and Day, 2009; Nel and Van Zyl, 2010; Hall and Klitgaard, 2011; Murphy and Hall, 2011; Tverberg, 2012.).

Our Human Macroecology Group has documented how economic development depends on the rate of energy use (Brown et al., 2011; see also references above). As indexed by Gross Domestic Product (GDP), the level of economic development across modern nations varies by nearly three orders of magnitude, from less than \$250 per capita in the poorest countries, such as Somalia, Burundi, and Congo-Kinshasa to more than \$85,000 per capita in the wealthiest, such as Luxembourg, Bermuda, and Norway (The Economist, 2013). There is a strong correlation between per capita GDP and per capita energy use (Fig. 1a). Energy use varies by about two orders of magnitude. In the poorest countries it is barely more than the 100 watts of human biological metabolism. In the richest countries it is more than 10,000 watts, because human metabolism has been supplemented more than 100-fold from exogenous sources, mostly fossil fuels (Brown et al., 2011). Temporal trends over the last few decades show a similar relationship between economic development and energy use (Fig. 1b). From 1980 to 2005 most countries experienced economic growth, accompanied by commensurate increases in energy use. In the few countries where GDP declined, energy consumption usually decreased as well. During the last decade economic growth was especially pronounced in the BRIC countries (Brazil, Russia, India, and China). Fig. 2 contrasts consumption of energy and other resources between 2000 and 2010 for China, where GDP increased more than 15% per year, and the US, where GDP grew by less than 4%.

The causal link between energy use and economic development is easy to understand. Just as a growing human body needs increasing amounts of food, a growing economy needs increasing quantities of energy, water, metal ores, and other resources. Fig. 1a shows that per capita energy use scales with approximately the 3/4 power of per capita GDP across nations (i.e., the slope of the log–log plot in Fig. 1a is 0.76). This means that the rate of energy use scales with GDP on a per individual basis similarly to the 3/4 power scaling of metabolic rate with body mass in mammals, often referred to as Kleiber's rule (Kleiber, 1961). This similarity may not be coincidental. Both mammalian bodies and modern economies are sustained by consumption of energy supplied through complex branching networks (West et al., 1997). Regardless of whether the approximately 3/4 power scaling is due to a deep causal relationship or an amazing coincidence, both relationships reflect similar