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Macroecology Meets Macroeconomics: Resource Scarcity and Global Sustainability

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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.

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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 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. (2013) and Hall and Day (2013), and in other publications by these and other authors (e.g., Odum, 1971;Smil, 2008; 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, 2012). 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 underlying causes – the energy cost of maintaining the structure and function of a large, complex system.

The relationships in Fig. 1a can be used to develop future scenarios (Table 1; Brown et al., 2011). We emphasize that these are not predictions; they are simply extrapolations of current patterns of energy use and GDP. Nevertheless, the implications of these scenarios for “sustainable development” are sobering. As classically defined in the Report of the Brundtland Commission (1987, see also United Nations Development Programme, 2011), "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs". According to Table 1, to bring the current global population up to a US standard of living would require nearly a 5-fold increase in energy consumption, an obvious impossibility. Global energy use could potentially be reduced by 25% by offering everyone on Earth the current average Chinese standard of living, which could theoretically be accomplished by increasing the per capita GDP of poorer countries and decreasing it in richer countries (Brown et al., 2011). Note that China, far from being content with its current standard of living, is striving to grow its GDP as fast as possible (Klare, 2012; Moya, 2012). More importantly, however, large increases in global energy consumption will be required to meet UN projected population and economic growth for 2025, just 12 years from now (Table 1).

What are the prospects for increasing energy production to meet the scenarios for future development? This is the subject of other papers in this collection and elsewhere. We simply point out that about 85% of current energy use comes from fossil fuels (37% from oil, 25% from gas, and 23% from coal; REN21, 2006). These are finite non-renewable resources. There is good evidence that global oil production has already peaked or will soon do so, and the reserves of gas and coal are being rapidly depleted. Recent increases in oil and gas extraction in North America using hydraulic fracturing technology (http://www.iea.org/newsroomandevents/pressreleases/2012/november/name,33015,en.html) have simply increased the rate of depletion of the finite stocks. Oil is especially valuable, because it has the highest energy density of any fossil fuel and hence cannot be substituted for in many uses. The problem of “peak oil” is not that this and other finite geological resources (such as metals, phosphate, and rare earths; see below) have been completely used up, but that the rich, easily exploited stocks have been depleted. The remaining reserves are increasingly scarce, dispersed, difficult to extract, and far from human habitation, so the costs of maintaining even current rates of supply are increasing (e.g., Murphy and Hall, 2011; Tverberg, 2012). Nuclear energy currently accounts for about 6% of global energy use and all renewable energy sources together account for only about 9%. Because large quantities of energy and material resources are required to develop these alternative energy sources (see below and Hall and Klitgaard, 2011; http://physics.ucsd.edu/do-the-math/2011/10/the-energy-trap) prospects for increasing energy production sufficiently to meet projected demand are severely limited -- and achieving them in the critical next few decades is highly unlikely.

4. Other resources

Energy is not the only essential resource that has been depleted to the point where it is becoming limited. To return to the biological analogy, just as a human being requires not only food energy but also water, protein, vitamins, minerals, clothing, and shelter to grow and survive, so the modern industrial-technological-informational economy requires not only energy but also water, cement, phosphate, metals, and rare earths. Rates of use of all these resources are also closely correlated with energy use and GDP (Brown et al., 2011).

Many of these resources have been consumed to the extent that scarcity has resulted in reduced per capita consumption (Burger et al., 2012; Klare 2012; Moyo, 2012). Fig. 3 shows trajectories of global consumption since 1960. Per capita use of all these resources, except for iron, cement, and perhaps molybdenum have peaked, often decades ago. Some of these, such as fossil fuels, metal ores, and phosphate, are non-renewable, and humans have already extracted and burned or dispersed the richest reserves. Others, such as fresh water, fisheries, and wood, are potentially renewable but are being used at unsustainable rates (Wackernagel and Rees, 1998; Rockström et al., 2009; Burger et al., 2012; Hengeveld, 2012; Klare, 2012; The Royal Society, 2012; Ehrlich and Ehrlich, 2013). Experts in various commodities are beginning to warn not only about peak oil (Hubbert, 1949; Hirsch et al., 2006; Sorell 2010) but also about peak water and the over-harvesting of forests and fisheries (Gleick and Palaniappan, 2010; Foley et al., 2011). It is clear that the Bruntland Commission’s (1987) definition of sustainable development has already been violated, because resource use to meet “the needs of the present” has already compromised “the ability of future generations to meet their own needs”.

All of the natural resources in Fig. 3 and many others are important for contemporary humans. Some are required just to keep the present population alive, whereas others are essential for the modern industrial-technological-informational economy. The finite amount of arable land and declining stocks of fresh water, fish (a major protein source), phosphate (an essential fertilizer), and wood (a source of fiber for fuel and housing) mean that major changes in food and shelter will be required to meet projected population growth. Some suggest that the “urban transition”, the trend for an increasing proportion of the population to reside in cities, will allow the Earth to accommodate continued population growth through more efficient use of space and resources (see Ash, 2008 and the following special issue of *Science*). However, the increased urban populations will need to be fed by a smaller proportion of farmers from a fixed amount of arable land. For rural food production to keep pace with increased urban consumption will require large investments of energy to power machines, and of water and fertilizers to increase yields (Wackernagel and Rees, 1998; Brown, 2012). Futuristic scenarios in which cities produce a substantial proportion of their own food (Ehrenberg, 2008), need to be subjected to rigorous biophysical analysis. Even if this were theoretically possible, it may not be feasible, because the necessary changes in urban architecture and landscapes will require large energy and material subsides.

Large quantities of fresh water and minerals, including copper, iron, molybdenum, nickel, cadmium, platinum, gold, silver, and rare earths are used in industry, including hi-tech electronics and optics. In addition to industrial uses, increased quantities of some minerals will be required to switch from fossil fuels to renewable energy sources. For example, increased deployment of solar energy will require increased use of silicon or cadmium for photovoltaic cells; copper, silver, or other non-magnetic metals for electrical transmission lines; and lead, zinc, nickel, cadmium, or lithium for storage batteries. The quantity of each of these elemental substances in the Earth’s crust is fixed. Some of them, such as silicon, lead, and zinc, are relatively abundant, but others are much scarcer. The richest ores near populations have long since been mined, and their contents discarded in landfills and otherwise dispersed. Even though some recycling and subsititution will often be possible, increasing quantities of energy and money will have to be expended to find, collect, and purify increasingly scarce minerals in order to maintain supply to meet ever-increasing demand. The result is a rapidly intensifying global race to corner the market (Klare, 2012; Moyo, 2012). For example, China's rapid industrialization and economic growth in the first decade of the 2000s entailed large increases in consumption of copper and iron as well as energy from fossil fuels (Fig. 2).

5. Quality of life

Some suggest that level of economic development, often measured as per capita GDP, is a poor measure of what really matters. GDP quantifies the market value of all final goods and services produced in a country per unit time, usually one year. Economists and many others use it as the best available, but admittedly imperfect, index of economic growth and development. There is disagreement, however, on how well GDP measures standard of living (e.g., Dasgupta and Weale, 1992; United Nations Development Programme, 1990). As an alternative to GDP, some social scientists have promoted the Human Development Index (HDI) or the Genuine Progress Indicator (GPI), which include factors such as life expectancy, education, income distribution, environmental costs, crime, and pollution (Daly and Cobb 1994; Klugman, 2010; Posner and Costanza 2011; United Nations Development Programme, 2011; Kubiszewski et al. 2013).

It has been suggested that the quality of life can be increased with minimal economic impact by eliminating inefficiencies in resource use and extravagant consumption by the wealthiest citizens of the wealthiest nations (e.g., Diamandis and Kotler, 2012; Jackson, 2012). There is undoubtedly some room for economizing, by both increasing efficiency and eliminating unnecessary consumption. Energy efficiency can be increased by stricter fuel standards for automobiles, better insulation of buildings, improved mass transit, and so on. Substitution, such as renewable energy for fossil fuels and other conductors for copper wires, can reduce the depletion of some severely limited resources. Water can be saved by behavioral and technological changes that reduce applications to industry and human landscapes and increase water use efficiency of agriculture. Recycling can add to the supply of both abiotic (metal ores, phosphate, water) and biotic (wood fiber) resources, reducing the depletion of the remaining natural stocks. Many kinds of conspicuous consumption, such as gas-guzzling automobiles, lavish climate-controlled houses and workplaces, giant home theatre systems, smartphones, jet-set travel, and other extravagances, are obviously not essential to a happy, healthy lifestyle.

Nevertheless, there is little support for the proposition that large reductions in economic activity, and hence in resource consumption, can be achieved without sacrificing what really matters – quality of life (e.g., Costanza et al., 2009; Jackson, 2012; Wijkman and Rockström, 2013; but see Kubiszewski et al. 2013). The HDI and many variables that can be associated with quality of life are closely correlated with GDP (Fig. 4; see also Kelley, 1991). This is not surprising, because all of these variables tend to co-vary with each other, and also with rates of energy and material resource use (Brown et al., 2011). The global per capita GPI peaked in 1978 (Kubiszewski et al. 2013), about the same time that per capita use of oil and several other resources peaked (Fig. 4; Burger et al. 2012) and the global

Ecological Footprint exceeded global Biocapacity (http://www.footprintnetwork.org/en/index.php/GFN/blog/today_is_earth_overshoot_day1). There are statistical issues with the relationships shown in Fig. 4: problems of data quality and standardization of measurements across countries, whether the variables on the Y-axis are scaled linearly or logarithmically, and how to account for the observed variation (i.e., the correlation coefficients). Nevertheless, these relationships go beyond mere correlations to indicate powerful mechanistic processes that require natural resources for economic growth and development. A developed economy with concomitant high rates of energy and other resource use is required to maintain infrastructure, eradicate poverty, and produce drugs, vaccines, computers, and cell phones. Not only money, but also energy and materials are required to educate teachers, scientists, engineers, and physicians, to build and maintain the infrastructure of housing, workplaces, and transportation and communication facilities, and to train and employ all the people in the public and private service industries. Few people would voluntarily go back to the average lifestyle and standard of living in 1978 when the GPI peaked, even if it were possible to do so. The paper by Day et al. in this special feature (2013) shows how energy shortages will first and most severely reduce discretionary income, as people restrict expenditures to essential food and shelter. Discretionary income provides not only dispensable luxuries but also most things that we associate with quality of life: healthcare, education, science and the arts, travel and recreation. As the economist Milton Friedman is famous for saying, “There is no such thing as a free lunch.” Reductions in energy and material resource use will necessarily require sacrifices in quality of life.

6. Future prospects

So what does the future hold: an imminent end to population and economic growth because we have exceeded the biophysical limits of the finite Earth or a new period of growth and prosperity stimulated by technological innovation; a Malthusian reckoning or a Cornucopian rescue? Currently the global population comprises 7.1 billion people whose standards of living range from abject poverty to extravagant wealth but on average are comparable to typical average residents of China, Indonesia, and Algeria (HDI = 0.67–0.70: The Economist, 2013). Future projections of population and economic growth are widely variable and constantly being revised. Optimistic Cornucopian “sustainable development” scenarios for 2050 forecast a global population of 9–10 billion, 3–4% economic growth, and substantial reduction of poverty and disease in developing countries (e.g., International Council for Science, 2002; Millennium Ecosystem Assessment, 2005; Sachs, 2005; United Nations World Population Prospects, 2010; Foley et al., 2011; DeFries et al., 2012; Diamandis and Kotler, 2012). These are countered by pessimistic Malthusian scenarios (e.g., Meadows et al. 2004; Bardi, 2011; Brown et al., 2011; Burger et al., 2012; Hengeveld, 2012; Ehrlich and Ehrlich, 2013), which suggest that a catastrophic crash is inevitable because the size of the present population and extent of current economic development already far exceed sustainable levels.

One thing is clear: ultimately Malthusian limitations must occur. It is mathematically, physically, and biologically impossible for continual exponential growth in population size and resource use in a finite environment. At some point, food shortages will limit population size or scarcity of other resources will halt economic growth and development. The only questions are when will this occur and what kind of adjustments will it entail?

The answers are uncertain, and we will not make predictions. Global civilization and its economy are complex dynamic systems (e.g., Tainter, 2011; Barnosky et al., 2012). Other such systems include hurricanes, forest fires, pandemic diseases, and the stock market. Such systems are composed of many components of many different kinds that interact with each other and with the extrinsic environment on multiple spatial and temporal scales. Their dynamics, driven by a combination of internal feedbacks and external forcings, are highly unpredictable.

We see several lines of evidence that the limits to growth and the concomitant declines in population and economy may be imminent. The first is the fact that per capita use of many resources has been declining for decades (Burger et al. 2012; Fig. 3). Some may see the decrease in per capita consumption as encouraging evidence of increased efficiency. But such “efficiency” is a response to demand increasing faster than supply, with corresponding increases in price. Abundant solar and wind energy have always been available, but they were not heavily used so long as there were abundant supplies of cheap fossil fuels with high energy density. Similarly, increased recycling of metals and wood fiber is an adaptive response to depletion of the richest natural stocks.

Second, contrary to conventional wisdom, most projections in *The Limits to Growth* have been accurate. Re-examination of the computer simulation model of Meadows et al. (1972) indicates that nearly all predictions, except for food production, remained on track at least through the early 2000s(Meadows et al., 2004; Bardi, 2011, but see Turner, 2008). The widespread famines and resulting global population crash predicted by Ehrlich (1968) and Meadows et al. (1972) were averted primarily by the green revolution: applications of agricultural innovations that increased food production. But the critical technologies – genetic modification, use of supplemental fertilizers and water, and mechanization, implemented in the 1980s and 1990s, not only rely on fossil fuel inputs but also are facing diminishing returns in energy efficiency per unit yield (Tilman et al., 2002). Now the world is again faced with a crisis of food scarcity, with frequent regional famines, thousands of deaths annually, and consequent social and political instability (Ehrlich and Ehrlich, 2013).

Third, despite the emphasis of economists, policymakers, and politicians on growth, the global economy has not recovered from the recession of 2008. The magnitude of the crash and the sluggish recovery suggest that, despite abundant unemployed labor, large amounts of corporate capital, and continuing technological innovation, factors outside conventional economic models are restricting growth. There is a surplus of human and monetary capital, but growth is limited by natural capital of energy and raw materials. The economic and political establishments have been slow to recognize and respond to the link between economy and resources. Implicitly, however, there is increasing recognition of the need for natural resources, especially energy, to fuel economic growth and development. There is also increasing recognition that the needed increases in resource production and consumption at the global scale have not occurred.

Finally, there has been far too little scientific, political, and media attention to the question, What is the carrying capacity of the earth for human beings? As Cohen (1995) has emphasized, the answer to the question “How many people can the Earth support?” depends on many things, but most importantly on standard of living and concomitant resource use. The present situation would probably not be so dire if meaningful action had been taken when the question of carrying capacity was raised by Ehrlich (1968), Meadows et al. (1972), and others decades ago. Now this has become the most important scientific and social issue of our time. It should be addressed by our greatest talents, including natural and social scientists, politicians and policymakers, and lay people. Unfortunately, many of the underlying issues, such as population control, equality of economic opportunity, and climate change, are politically charged. Both politicians and the public seem reluctant to confront the specter of a pessimistic future.

Our own assessment is that it is impossible for the Earth to continue to support the present number of people living their current lifestyles. The growth paradigm of traditional economics is no longer compatible with the biophysical carrying capacity of the finite Earth. The economic crash of 2008 and the lack of recovery are due, not to deficiencies in economic policy, but to increasing scarcity of natural resources; not to matters of traditional economics, but to fundamental biophysical constraints on human ecology. Substantial, sustained economic growth and development is no longer possible, because, for the first time in history, human resource demands exceed global limits on resource supply. In the language of ecology, contemporary humans have exceeded the carrying capacity of the Earth. Unsustainable resource consumption has created a large bubble of population and economy. The bubble cannot keep on increasing: it must either deflate gradually or it will burst. This is not an optimistic assessment, but it must be taken seriously (Meadows et al. 2004; Bardi, 2011; Brown et al., 2011; Burger et al., 2012; Hengeveld, 2012; Ehrlich and Ehrlich, 2013; Wijkman and Rockström, 2013). Wishful thinking, denial, and neglect will not lead to a sustainable future for human civilization.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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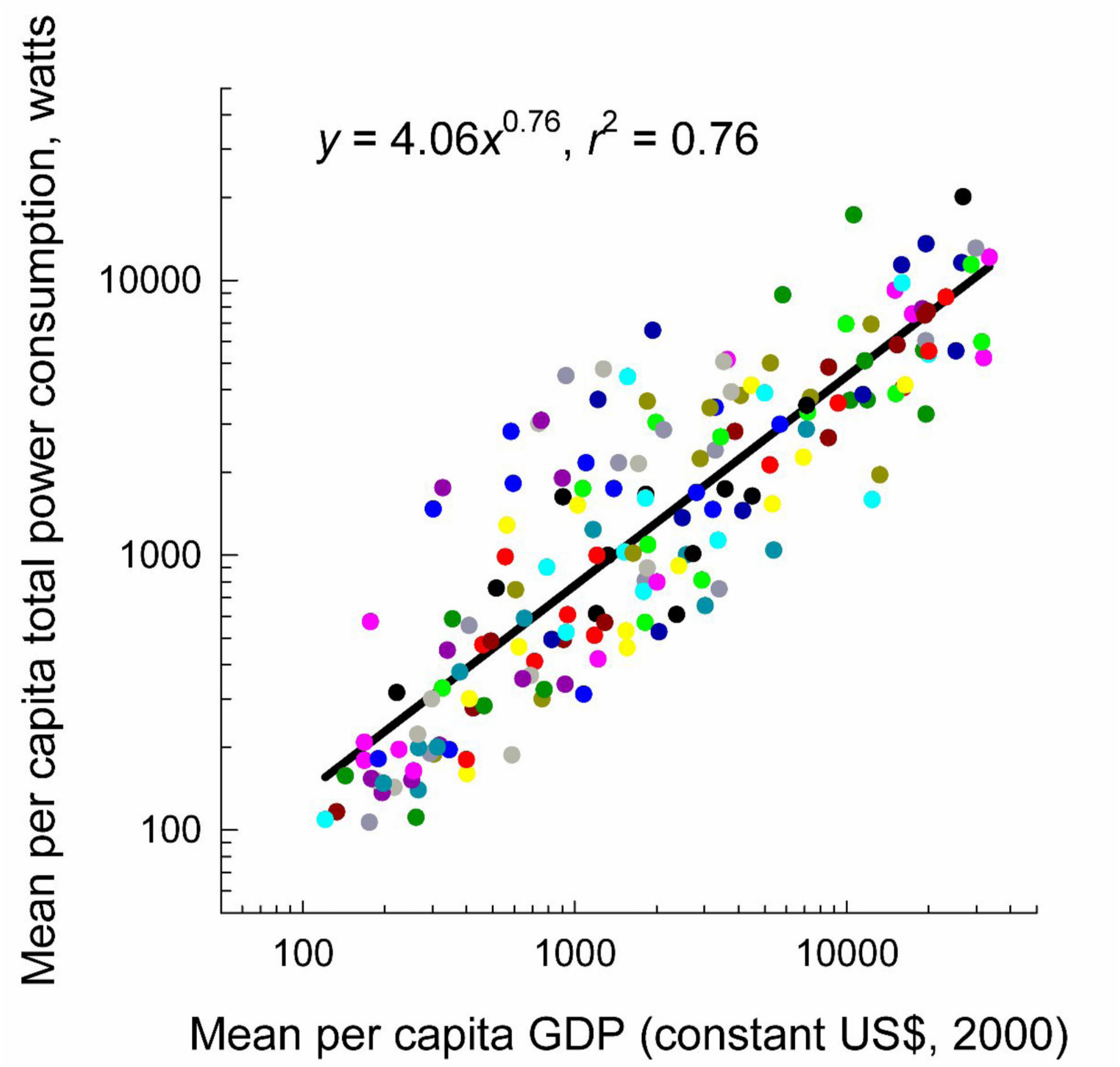

$y = 4.06x^{0.76}$, $r^2 = 0.76$
Mean per capita total power consumption, watts
10000
1000
100
100
1000
10000
Mean per capita GDP (constant US$, 2000)

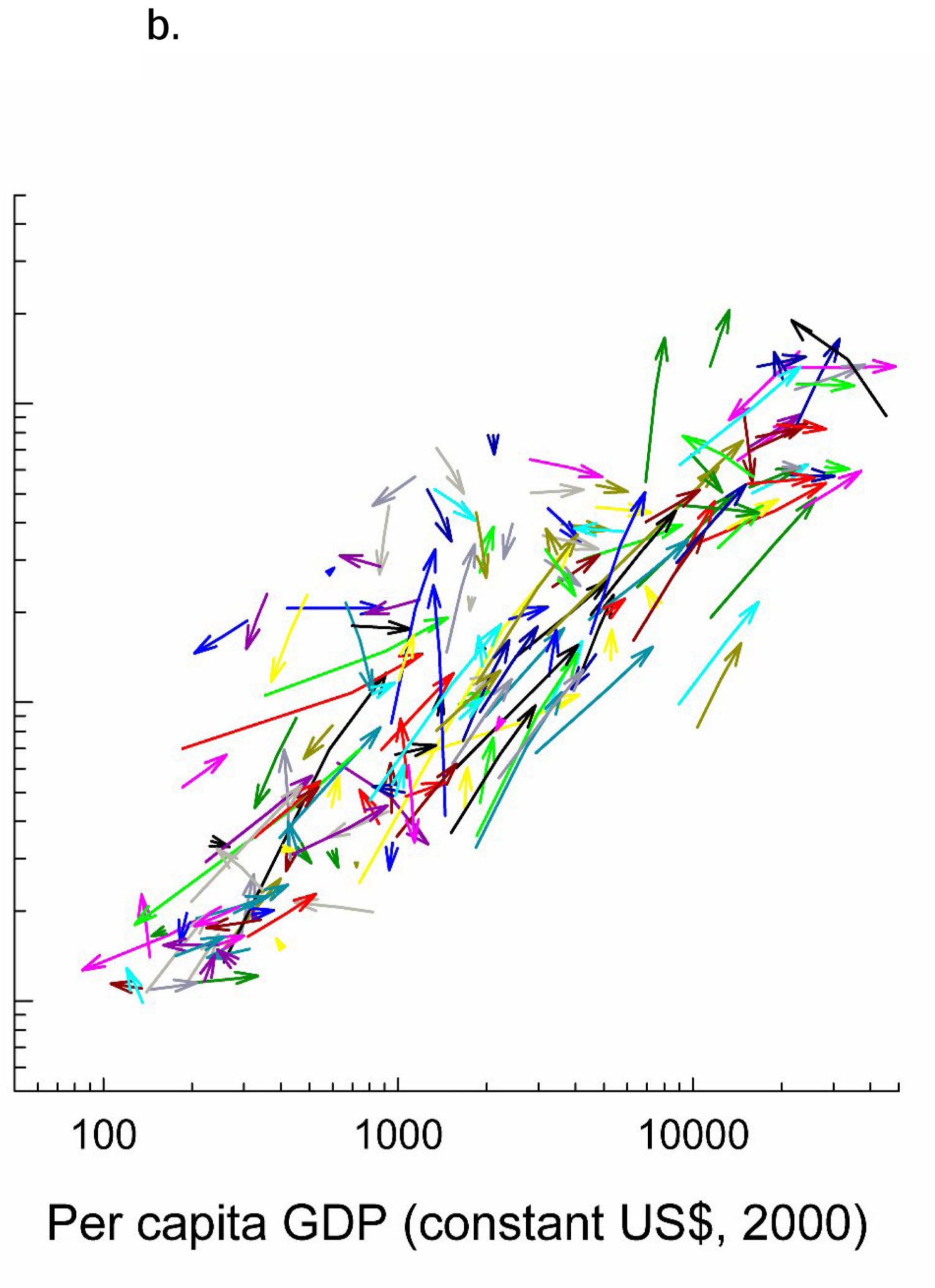

Fig. 1.

Relationships between per capita energy use and per capita GDP: a) Across countries, with each point representing the average energy consumption and the average GDP from 1980–2005; b) over time, with each arrow showing the net change from 1980 to 2005. Note that per capita energy consumption scales as the 0.76 power of GDP (a), and the changes in energy consumption over the 25 years (b) parallels this scaling relationship. Replotted using data compiled by Brown et al. (2011).

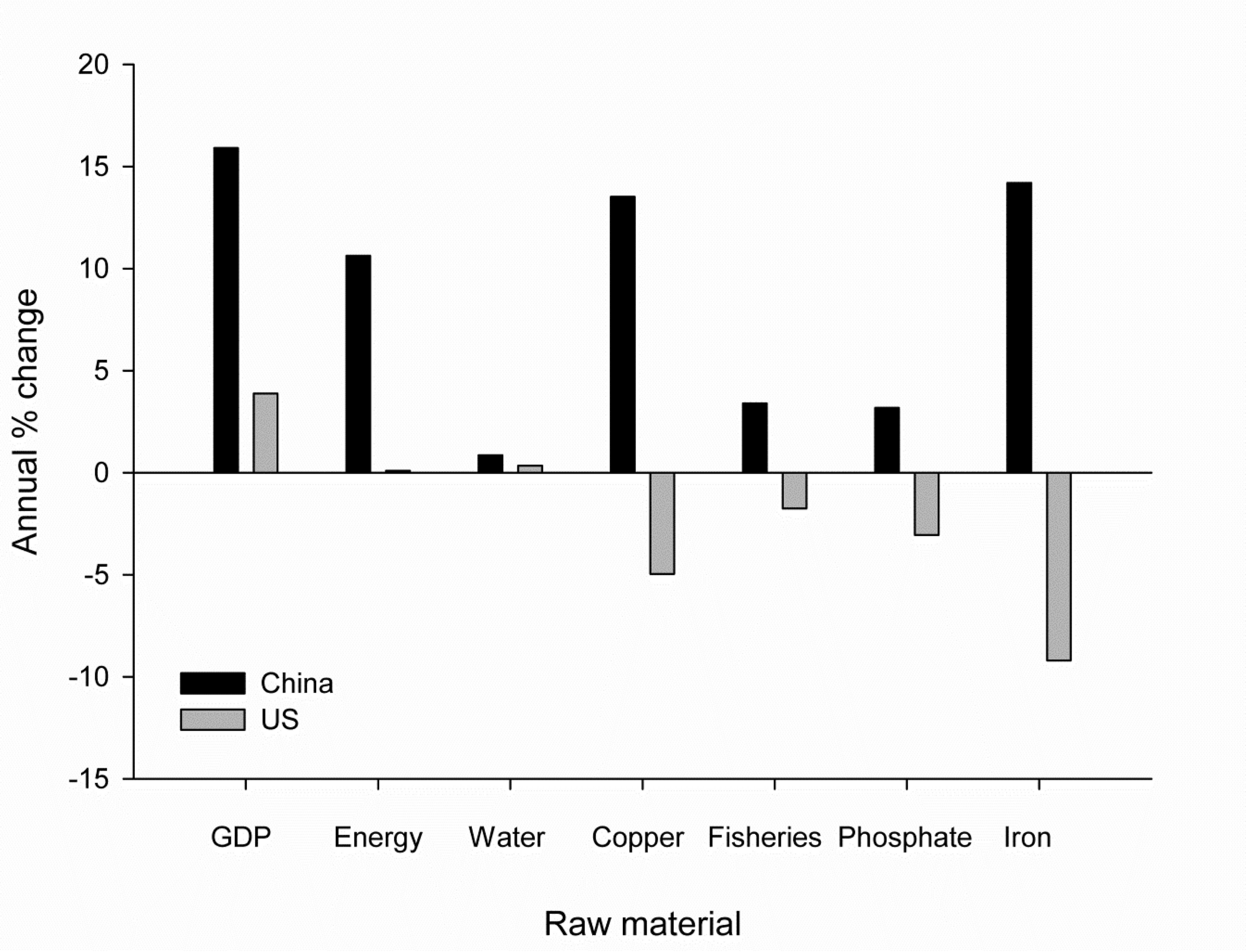

Fig. 2.

Annual percent change in GDP and resource consumption for the US and China from 2000 to 2010. China's economic growth of more than 15% per year was accompanied by commensurate increases in consumption of energy, water, metals, phosphate, and fisheries. Much slower growth of the US economy consumed much less of all these resources. Some of the changes in individual commodities also reflect trends due to globalization. For example, the shift in manufacture and export of electronics from the US to China is reflected in the decrease copper consumption in the US and the large increase in China.

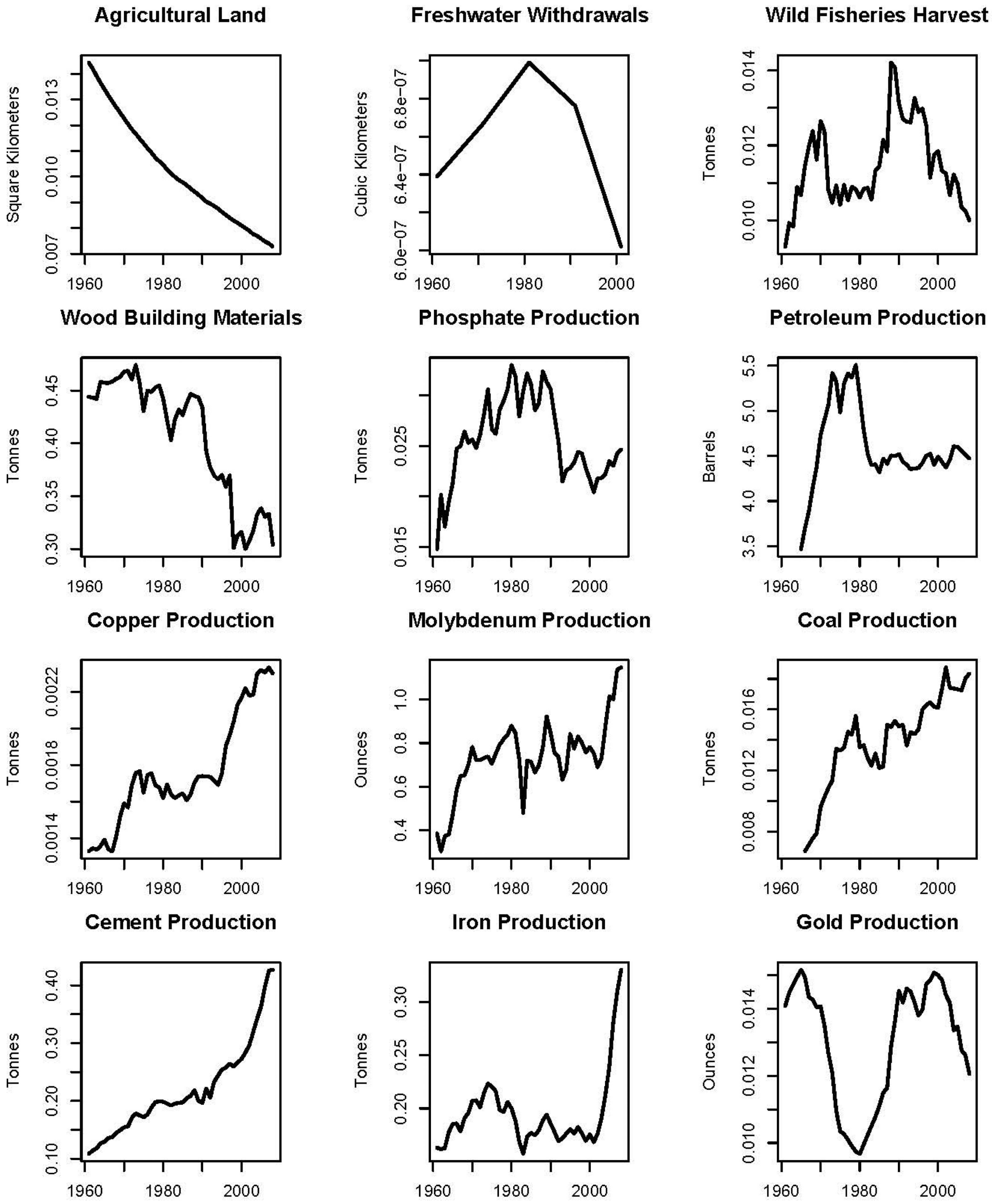

Fig. 3.

Trajectory of per capita extraction and consumption of natural resources since the 1960s. Note that per capita supplies of all these resources, except for iron and possibly molybdenum and cement, have peaked, often decades ago, and are now declining. Data sources: per capita values represent the total values divided by global population size as reported by the World Resources Institute (http://earthtrends.wri.org/). Individual sources for global production/consumption values are as follows: Agricultural land in km^2 is from the World Development Indicators Database of the World Bank (http://data.worldbank.org/

data-catalog/world-development-indicators) and represents the sum of arable, permanent crop, and permanent pasture lands. Freshwater withdrawal in km^3 from 1960, 1970, 1980, and 1990 is from UNESCO http://webworld.unesco.org/water/ihp/db/shiklomanov/part%273/HTML/Tb_14.html) and for 2000 from The Pacific Institute (http://www.worldwater.org/data.html). Wild fisheries harvest in tonnes is from the FAO Fishery Statistical Collection Global Capture Production Database http://www.fao.org/fishery/statistics/global-capture-production/en) and is limited to diadromous and marine species. Wood building material production in tonnes is based on the FAO ForeSTAT database (http://faostat.fao.org/site/626/default.aspx), and represents the sum of compressed fiberboard, pulpwood+particles (conifer and non-conifer [C & NC]), chips and particles, hardboard, insulating board, medium density fiberboard, other industrial roundwood (C & NC), particle board, plywood, sawlogs+veneer logs (C & NC), sawn wood (C & NC), veneer sheets, and wood residues. Phosphate, copper, molybdenum, pig iron, gold, and combustible coal production data in tonnes is based on World Production values reported in the USGS Historical Statistics for Mineral and Material Commodities (http://minerals.usgs.gov/ds/2005/140/). Global coal production data is limited to 1966–2008. Petroleum production in barrels from 1965 to 2008 is based on The Statistical Review of World Energy http://www.bp.com/sectiongenericarticle800.do?categoryId=9037130&contentId=7068669) and represents all crude oil, shale oil, and oil sands plus the liquid content of natural gas where this is separately recovered. These data are reported in 1,000 barrels/day, and were transformed to barrels per capita per year. GDP in 1990 US dollars are from the World Resources Institute (http://earthtrends.wri.org/). All data were accessed May 2011 to October 2012. After Burger et al. (2012) with new graphs for iron, molybdenum, and gold added.

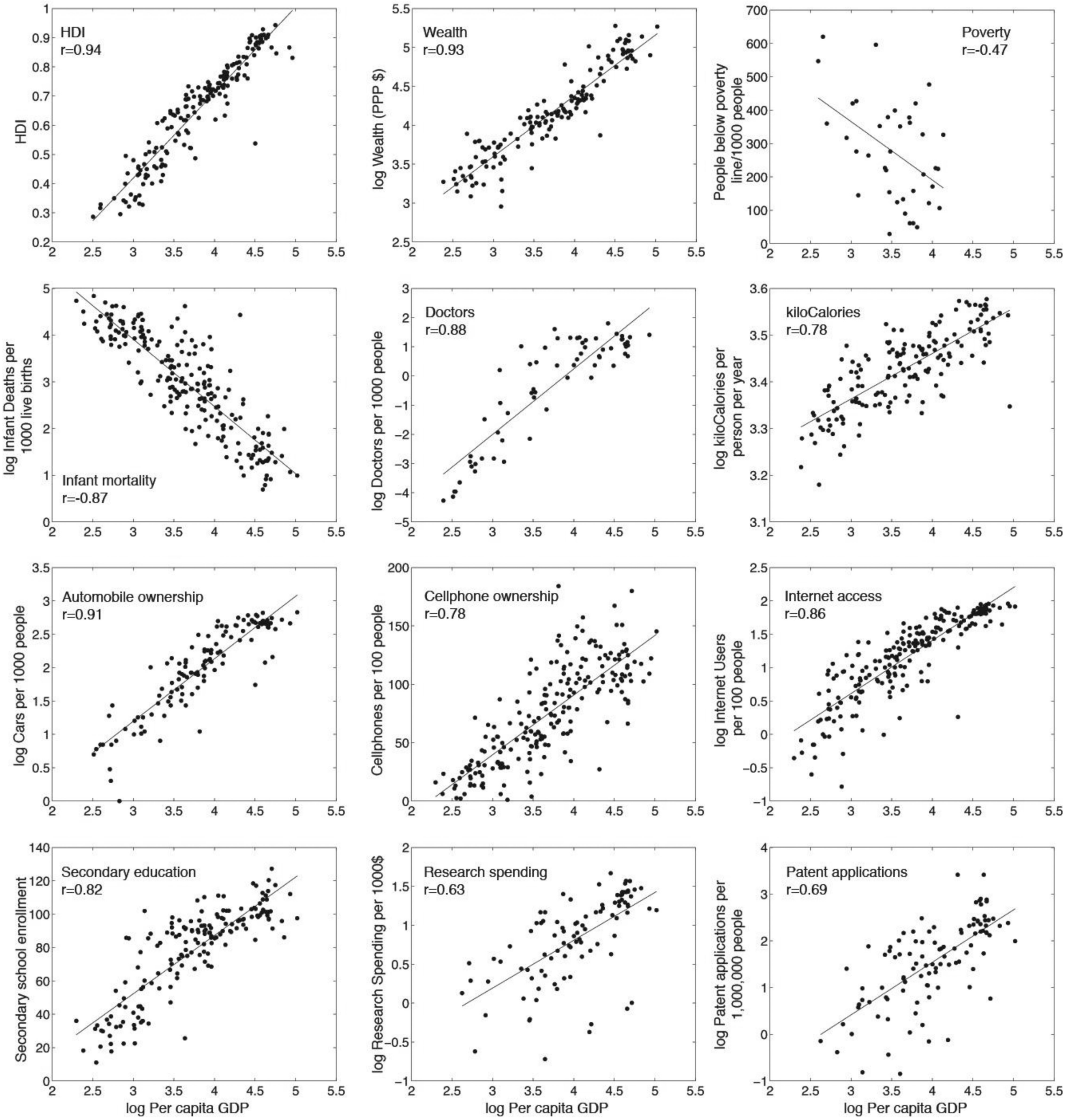

Fig. 4.

Variation across countries in relationships between GDP and variables that reflect standard of living and quality of life. First row: overall standard of living: A) Human Development Index (HDI), B) per capita wealth, C) poverty; second row: D) health: infant mortality, E) doctors, F) calories in diet; third row: technology: G) cars, H) cell phones, I) internet users; fourth row: education and research: J) secondary education, K) research spending, L) patents. In all cases each data point represents the value for a country, GDP is scaled logarithmically and plotted on the x-axis, the other variables are either log transformed or not, depending on which gives better fit, and correlation coefficients are given. Variables are either per capita or per hundred or thousand population as in the original source. Note that all variables are well correlated with GDP per capita, although the goodness of fit and exact form of the relationships vary. Data from http://databank.worldbank.org/data/home.aspx, accessed May 2011 to October 2012.

Table 1

Current global energy use and projected energy requirements to meet alternative scenarios of population growth and economic development. These are based on extrapolating the relationship (correlation line) in Fig. 1a. The first column gives total global annual energy requirements in exajoules (EJ = 10^{18} joules) and the second column gives the factor of increase relative to current consumption. So, for example, to bring the current world population up to a US standard of living would require an approximately 5-fold increase in global energy use, and to provide the entire world with a current Chinese lifestyle in 2025, incorporating UN projected population and economic growth, would require an approximately 2-fold increase. After Brown et al., 2011; for sources and calculations see www.jstor.org/stable/10.1525/bio.2011.61.1.7.

Scenario	**Energy requirement**	
	EJ	**factor**
World current	524	1.0
U.S. lifestyle	2440	4.7
Chinese lifestyle	392	0.75
Current trends to 2025*	1142	2.2
U.S. lifestyle in 2025*	5409	10.3
Chinese lifestyle in 2025*	848	1.6

*Assumes 2025 world population of 8 billion and 3.8% per year increase in global GDP.