Conservation Biology

Essay

The Impending Peak and Decline of Petroleum Production: an Underestimated Challenge for Conservation of Ecological Integrity

BÁLINT CZÚCZ,* JOSEPH P. GATHMAN,† AND GUY R. McPHERSON‡

*Department of Plant Ecology, Institute of Ecology and Botany of the Hungarian Academy of Sciences, 2163 Vácrátót, Hungary, email czucz@botanika.hu

†Department of Biology, University of Wisconsin–River Falls, River Falls, Wisconsin 54022, U.S.A.

‡Department of Ecology & Evolutionary Biology, School of Natural Resources & the Environment, University of Arizona, Tucson, Arizona 85721, U.S.A.

Abstract: *In the last few decades petroleum has been consumed at a much faster pace than new reserves have been discovered. The point at which global oil extraction will attain a peak ("peak oil") and begin a period of unavoidable decline is approaching. This eventuality will drive fundamental changes in the quantity and nature of energy flows through the human economic system, which probably will be accompanied by economic turmoil, political conflicts, and a high level of social tension. Besides being a geological and economic issue, peak oil is also a fundamental concern as it pertains to ecological systems and conservation because economics is a subsystem of the global ecosystem and changes in human energy-related behaviors can lead to a broad range of effects on natural ecosystems, ranging from overuse to abandonment. As it becomes more difficult to meet energy demands, environmental considerations may be easily superseded. Given the vital importance of ecosystems and ecosystem services in a postpetroleum era, it is crucially important to wisely manage our ecosystems during the transition period to an economy based on little or no use of fossil fuels. Good policies can be formulated through awareness and understanding gained from scenario-based assessments. Presently, most widely used global scenarios of environmental change do not incorporate resource limitation, including those of the Millennium Ecosystem Assessment and the Intergovernmental Panel on Climate Change. Considering the potential magnitude of the effects of peak oil on society and nature, the development of resource-constrained scenarios should be addressed immediately. Ecologists and conservation biologists are in an important position to analyze the situation and provide guidance, yet the topic is noticeably absent from ecological discussions. We urge politicians, corporate chief executives, thought leaders, and citizens to consider this problem seriously because it is likely to develop into one of the key environmental issues of the 21st century.*

Keywords: ecosystem services, EROI, fossil fuels, global change, impact assessment, maximum empower, peak oil, vulnerability assessment

El Inminente Pico y Declinación de la Producción de Petróleo: un Reto Subestimado para la Conservación de la Integridad Ecológica

Resumen: *En décadas recientes el petróleo ha sido consumido a un ritmo mucho más rápido que el desubrimiento de nuevas reservas. Se aproxima el punto en el que la extracción global de petróleo alcanzará un pico ("cénit del petróleo") y comenzará un período de declinación inevitable. Esta eventualidad producirá cambios fundamentales en la cantidad y naturaleza de los flujos de energía en el sistema económico humano,*

Paper submitted February 25, 2009; revised manuscript accepted January 19, 2010.

Conservation Biology, Volume 24, No. 4, 948–956

DOI: 10.1111/j.1523-1739.2010.01503.x

que probablemente estarán acompañados por confusión económica, conflictos políticos y un alto nivel de tensión social. Además de ser un tema geológico y económico, el cénit del petróleo también es una preocupación fundamental ya que involucra sistemas ecológicos y conservación porque la economía es un subsistema del ecosistema global y los cambios en los comportamientos humanos relacionados con la energía pueden llevar a un amplio rango de efectos sobre los ecosistemas naturales, desde uso excesivo hasta abandono. A medida que es más difícil satisfacer las demandas de energía, las consideraciones ambientales pueden ser fácilmente desatendidas. Debido a la vital importancia de los ecosistemas y de los servicios del ecosistema en una era postpetróleo, es crucialmente importante manejar nuestros ecosistemas con sensatez durante el período de transición a una economía basada en poco o ningún uso de combustibles fósiles. Se pueden formular buenas políticas por medio de la concienciación y entendimiento obtenidos de evaluaciones basadas en escenarios. Actualmente, los escenarios globales del cambio ambiental más utilizados no incorporan la limitación de recursos, incluyendo los de la Evaluación de Ecosistemas del Milenio (EEM) y el Panel Intergubernamental de Cambio Climático (PICC). Considerando la magnitud potencial de los efectos del cénit del petróleo sobre la sociedad y la naturaleza, el desarrollo de escenarios constreñidos por los recursos debe ser atendido inmediatamente. Ecólogos y biólogos de la conservación están en una posición importante para analizar la situación y proporcionar directrices, sin embargo el tema está notablemente ausente de las discusiones ecológicas. Exhortamos a políticos, directores ejecutivos, líderes de opinión y ciudadanos a que consideren este problema seriamente porque es probable que se convierta en uno de los temas ambientales clave del siglo 21.

Palabras Clave: cambio global, cénit del petróleo, combustibles fósiles, empoderamiento máximo, EROI, evaluación de impacto, evaluación de vulnerabilidad, servicios del ecosistema

Introduction

Study of the flow and allocation of energy and materials through ecosystems is a core concern of ecosystem ecologists. Although many university textbooks present energy flows primarily in the context of natural ecosystems, some ecosystems scientists, such as Howard and Eugene Odum and their students, have proposed models that include human economic systems as subsets of natural ecosystems. They believe modern industrial economies are "techno-ecosystems" fed by energy-subsidized agroecosystems (Odum & Barrett 2005) that must obey fundamental laws of thermodynamics. Their model likens modern cities to highly energy-subsidized parasites that feed on a continual inflow of energy and material from the surrounding environment, while releasing large quantities of waste material back to that same environment. Just as a successful parasitic species does not kill its host population by overconsuming its resources, techno-ecosystems must "learn" to function within the energetic and material constraints imposed by the natural environment on which they depend.

Scientists have long warned society that the concept of continual growth on a finite planet is flawed and will result in some form of a decline driven by natural constraints (e.g., Meadows et al. 1972; Ehrenfeld 2005; Hall & Day 2009). Meanwhile, many economists have argued that resource limitations are nonexistent or irrelevant to economic growth (e.g., Simon 1996), but ecological economists have consistently pointed out that economic systems are constrained by the same biophysical limitations that constrain the ecosystems in which the economy functions (e.g., Georgescu-Roegen 1971; Costanza & Daly 1992). Although the planet's carrying capacity for humans is not presently known and is contingent on many factors, it is possible that many well-documented, global-scale resource and ecological problems are planetary indicators that humans are approaching, or have reached, carrying capacity. These troubling problems, which include climate change, ozone depletion, potable-water shortages, collapsing ocean fisheries, species extinctions, soil loss and nutrient depletion, point to increasing strains on human and nonhuman populations (e.g., Wackernagel et al. 2002; Meadows et al. 2004; Rockstrom et al. 2009).

A less recognized, but imminent, threat to the status quo of our society is "peak oil," which will soon be reached, if it has not been passed already. Peak oil will bring with it an end to the age of cheap oil (Campbell & Laherrere 1998; Heinberg 2003; Bentley & Boyle 2008). Peak oil refers to the point at which the annual rate of global oil extraction reaches a peak that is then followed by an inevitable decline in the annual extraction rate. This event, which occurs after approximately half the world's oil reserves have been consumed, means growth of oil supply is no longer possible, and supply constraints will drive up prices even if demand stabilizes. Nevertheless, due to rapid economic development in many parts of the world, demand is still growing quickly, and increasing resource nationalism of oil-producing countries also may contribute to higher oil prices (Hirsch 2008). The imbalance between oil extraction and demand can be considered the first concrete symptom of a growth-centered society reaching its limits, and these limitations will have tremendous consequences for western civilization. Because at present the functioning of society in developed countries is highly dependent on fossil fuels (e.g., Youngquist 1999; Hall et al. 2003; Hall & Day

2009), the coming oil shortage will challenge all industrial activities and therefore will have dramatic effects on ecosystems and nature conservation (Odum & Odum 2001; Heinberg 2003; Day et al. 2009).

Peak Oil

The concept of peak oil indicates that societies will encounter serious difficulties decades before all available oil has been extracted. The rate of extraction from oil fields approximates a bell-shaped curve when plotted against time, in which production starts to decline well before all resources are depleted. Historically, the first oil fields brought into production contained high-quality oil ("light, sweet crude") that was under high pressure relatively close to the surface. During the last 150 years, the most easily accessible oil sources have been used up, and despite enormous efforts, new discoveries have steadily declined since the early 1960s (Campbell & Laherrere 1998; Fig. 1). In 1956 after analyzing trends in new discoveries and the extraction curves of individual oil fields, oil-industry geologist M. King Hubbert formulated a model to predict the timing of the peak production of large areas. With his model Hubbert successfully predicted the peak of oil extraction in the conterminous United States by 1970 (Hubbert 1956, Fig. 1). Since then a number of oil-producing nations, including all industrialized countries, have reportedly reached peak production (WWI 2005). This indicates global oil extraction may not be far from peaking. In fact, application of Hubbert's model by some researchers indicates world oil extraction peaked in 2005 (Deffeyes 2005; Bentley & Boyle 2008; Fig. 2).

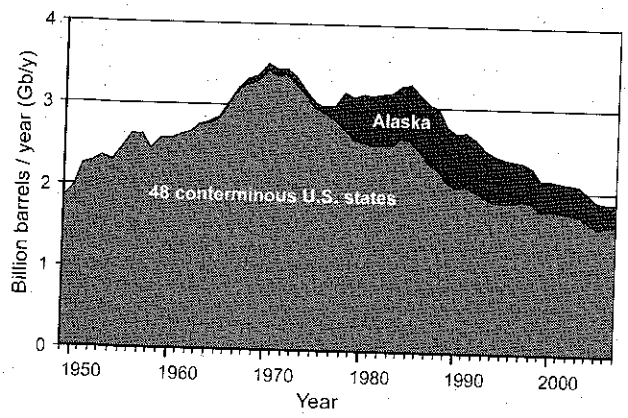

Figure 1. Historical production of crude oil in the United States between 1949 and 2007 (reflects Hubbert curve). The production peak in 1970 of the conterminous 48 states was followed by new exploration and development in Alaska, which only temporarily postponed the depletion trend (data from EIA 2008a).

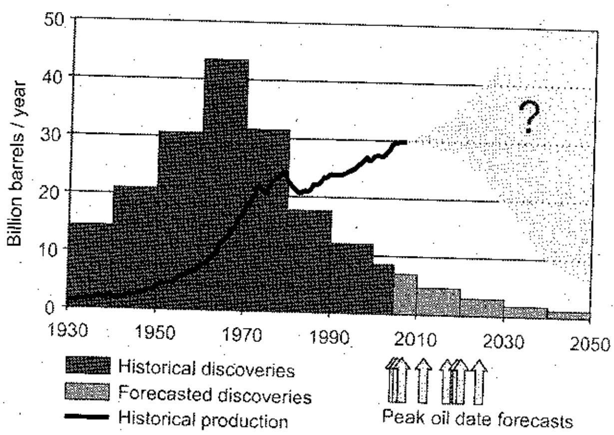

Figure 2. World oil discoveries (Campbell 2005) and production (Campbell 2005; BP 2008) 1930–2050 and forecasts of dates of peak oil (Bentley & Boyle 2008) (shaded area with question mark, indicates uncertainties in future oil production).

Although many other forms of energy are also consumed, the abundance, high energy concentration, and ease of extraction, storage, and transportation have made oil the fuel of choice for industrialized nations. There are no readily available or comprehensive alternatives to oil (Hirsch et al. 2005). Declining availability of oil constrains use of all fossil fuels because petroleum products are used to extract, deliver, and process all fuels and raw materials (and to manufacture "alternative" energy technologies) (Hirsch et al. 2005; Hall et al. 2008). Natural gas could serve as a substitute for many uses, but it also will have a peak-and-decline future similar to oil (Aleklett & Campbell 2003). Other fossil alternatives, such as tar sands, oil shales, and extra heavy oils (sometimes called nonconventional oils), and coal all have some significant drawbacks: either they are not technically feasible (no mature technology to produce effective substitutes in adequate quantity) or they are environmentally detrimental (large-scale strip mining and energy-and-water-intensive processing) (Salameh 2003). Although many argue that solar, wind, wave, and nuclear power can replace fossil fuels as energy sources, others state that these technologies are limited as substitutes because they are unlikely to meet the energy needs of modern societies in the foreseeable future due to problems of scale. The mass installation of solar panels and wind turbines, for example, is constrained by construction capacity, raw material availability, and, above all, energy: the large-scale infrastructural developments required for renewable or nuclear energy to become a major component in the global energy mix would require a significant portion of the world's remaining oil (Salameh 2003; Hirsch et al 2005; Goldstein

& Sweet 2007). Furthermore, uranium, as well as coal, may also be limited in the not-too-distant future, especially if consumption increases significantly (EWG 2006, 2007). Taking into consideration all energy alternatives, Hirsch et al. (2005) estimate that a seamless transition to a postpetroleum energy system would require 20 years of concerted effort before peak oil is reached. And even if the peak does not occur in the next 20 years, it is likely that the limitations of sustainable energy technologies will necessitate a lower level of global energy consumption than the current level (Odum & Odum 2006).

Consequences of shortfalls in oil production are illustrated by the aftermath of the U.S. oil peak in 1970, which led to the energy crises of the 1970s in which an approximately 5% decline in oil supply for a short period of time resulted in nearly a quadrupling of oil prices and a 3% decline in U.S. gross domestic product (GDP) (Hirsch 2008). The world's industrial economies are experiencing similar contractions today. In the past, however, it was possible to return to business as usual by exploiting foreign oil—an option that will not be available any longer. World oil dependency has increased since the 1970s. For example, for every 1 J of food energy consumed in the United States, up to 10 J of fossil energy have been used to produce it (Pfeiffer 2006). Hydrocarbons are feedstock for plastics, pharmaceuticals, fertilizers, and electronic components, but most importantly, oil is the most convenient and versatile fossil fuel, currently accounting for about 43% of the world's total fuel consumption and 95% of global energy used for transportation (IEA 2007).

Owing to its central role in modern western civilization, statements about future hydrocarbon availability lie within the fuzzy interface of science and policy, where uncertainties and value loadings are critical. Peak oil, similar to climate change, constitutes a typical postnormal problem (Funtowicz & Ravetz 1993) in which stakes are high, facts are uncertain, and values are in dispute. It is no wonder that both the timing and potential consequences of peak oil are still under intensive debate among scientific, industrial, and governmental communities. Similarly to early climate-change debates, the range of actors includes deniers, prophets of technocratic solutions, doubtful scientists, and enthusiastic nongovernmental organizations. Governmental agencies and multinational oil companies tend to paint an optimistic picture with respect to future oil availability (with peak oil occurring several decades in the future) (e.g., EIA 2008*b*) on the basis of optimistic estimates of the remaining reserves and assumptions that development of improved extraction techniques will be driven by increasing prices. Nevertheless, other more-critical calculations indicate that the global production peak is likely to occur in the near future or has already occurred (Bentley & Boyle 2008; Fig. 2), that the world is in the midst of a long and undulating plateau of oil availability, and that resource constraints may be causing increasing economic volatility. In fact, recent oil-extraction data indicate a relatively flat plateau from 2005 to 2008, despite the substantial increases in fuel prices of that period and the habitual pledges of the major producers to increase rates of extraction. The fuel price spike of 2008 may have played a considerable role in the formation of the current economic crisis (Hamilton 2009). Nevertheless, it is mostly the "when" and the pace-of-decline aspects of peak oil that are debated, not the eventual depletion of finite resources, which will unavoidably transform society at some point.

The Ecology of Peak Oil

Because ecological systems resemble social systems in many ways, ecologists have special roles to play in the analysis of and response to peak oil. Ecologists can contribute to the debate on peak oil by providing tools to describe energy flows through complex systems and clarifying the consequences of changing energy availability. It is no surprise that several concepts and methodologies in the peak-oil debate have their origins in the field of ecosystem energetics.

Net energy analysis (commonly called energy return on investment [EROI]) is perhaps the most important such energy-related issue (Hall 1972; Cleveland et al. 1984). (Sometimes EROI is written as EROEI, meaning energy return on energy invested.) This efficiency metric can provide considerable insight into the socioeconomic implications of the process of oil depletion (Odum 1973; Hall et al. 1986). Because the most accessible and most plentiful resources are depleted first, the EROI of energy production inevitably declines over time. For example, the EROI of global oil production has fallen from 100:1 to 20:1 (20 units energy return for 1 unit energy invested) during the last 80 years (Cleveland et al. 1984; Cleveland 2005; Gagnon et al. 2009). Declining EROI eventually will reach a fundamental threshold under which extraction becomes uneconomic, regardless of political devotion or market forces (Hall et al. 2009). Similarly, low EROI can undermine the viability of potential alternatives as well. For example, the production of ethanol from corn consumes nearly as much, or even more, energy than it provides as a vehicle fuel, depending on how many forms of input energy are included in the equation (Cleveland et al. 2006). Thus, corn-ethanol fuels have a slightly positive or even a negative EROI, which makes them particularly poor energy investments.

Another useful concept is that of emergy (embodied energy, sensu Odum 1996), which is a measure of the total amount of primary (solar) energy used to produce end-product delivered energy. Emergy can be used as a money-independent economic metric and has broad potential usage in environmental accounting (Costanza 1980; Odum 1996), but it is important well beyond its use in environmental accounting. Emergy offers conceptual insight in the evolution of complex systems. Originating initially from the works of Boltzmann (1974) and Lotka (1922), and further clarified by Odum, the maximum empower principle states, "in the self-organizational process, systems develop those parts, processes, and relationships that maximize useful empower" (Odum & Odum 2006: 23). The general applicability of this organizing principle is still under intensive debate, but as the mathematical and methodological background is being refined (e.g., Giannantoni 2002; Hau & Bakshi 2004) and supporting observational and experimental results are accumulating (e.g., Cai et al. 2006; Liu et al. 2008), it is becoming an increasingly prospective candidate as the 4th law of thermodynamics (Lotka 1922; Odum 1996). Accordingly, this law of evolution should also apply to socioeconomic systems because the free-market mechanisms of the economy effectively do the same thing for human systems (Liu et al. 2008). Securing and controlling maximal energy flows demand complex structures in nature and human societies. In fact, all residential, transportation and energy infrastructure, and sophisticated social structures, ensure maximal intake and use of the highest-quality energy available. Whereas abundant resources trigger growth, declining resource availability necessitates contraction accompanied by a changing pattern of resource use (Odum & Odum 2001, 2006). Such resource-induced contraction will have a tremendous impact on the future of humankind and nature, and on the complex relation between them.

Implications for Ecosystems and the Environment

How will peak oil affect nonhuman species, ecosystems, and ecosystem services? Naïvely, one could assume that fuel scarcity and the accompanying breakdown of energy-intensive solutions could bring instant relief to nature, but the reality likely will be more nuanced and depend partly on the policy choices formulated to address future challenges. Increasing concerns about energy, for example, might overcome concern for the environment and result in environmentally detrimental decisions at large and small scales. For example, extraction of oil from tar sands creates vast strip mines, uses large amounts of water and natural gas, and produces large quantities of pollution and CO_2 because of the relatively low energy efficiency of this process (Nikiforuk 2008). Other potential policy responses, such as extensive biofuel plantations, may have similar detrimental consequences (Pimentel et al. 2008).

Reducing fuel usage could bring significant changes to contemporary energy-intensive forest management and agricultural practices. Limited availability of fossil resources may cause an inverse "green revolution" and lead to less-intense agriculture (less technology and fertilizer and more human labor) and thus declining yields. Genetically modified crops may do well for a while, but due to their significant dependence on technology and global commercial networks they may not provide a long-term solution to declining yields. The future may see rather a return to traditional crop varieties (from among those still available) that are better adapted to nonintensive management. Decrease in available energy, however, need not be linear: "[D]uring the transition and turndown there could be frantic, competitive stripping of the environmental stocks needed for maximum production" of food and other resources (Odum & Odum 2006:26). Hasty and uncoordinated societal responses could damage ecosystems to such an extent that the resource base becomes degraded and the planetary carrying capacity is lowered, which would further stress human populations. If global food production falls due to declining fossil-fuel availability, humanity will be in an "overshoot" condition (Catton 1980; Price 1999; Duncan 2001). As all ecologists understand, the effects of overshoot on human societies could be dramatic, with many implications for resource-use patterns and conservation-related attitudes toward nature (Table 1).

Modern western society has used intensive management techniques powered by fossil energy to increase the supply of provisioning services (or ecosystem goods, such as food and fiber production) at the expense of other services (such as pollination, water regulation, and

Table 1. Potential implications of peak oil evaluated from the perspective of conservation biology (grouped by sector).

Sector	*Advantage*	*Disadvantage*
Agriculture	decrease in cultivation intensity	increase in area under cultivation (including biofuel production)
Forests	return to traditional forest management	overexploitation of forests for firewood
Tourism & transportation	decrease in spread of non-native species due to reduced tourism and travel	reduced tourism income for use in nature conservation
Climate change	decrease in CO_2 emissions (oil and natural gas production)	increase in CO_2 emissions (nonconventional oil and coal production)
Conservation policy	increasing focus on local sustainability	declining interest in large-scale conservation projects, weakening of international cooperation in conservation

aesthetic beauty) (MEA 2005). This problem is deeply rooted in the fundamentals of a growth-based market economy, which absorbs ecosystem goods relatively easily while treating all services (e.g., waste processing) and effects (e.g., pollution) that are not priced by the market as "externalities" belonging to "the commons." Observing the decline in these commons, their protection became the main focus of modern conservation. The move toward a low-carbon society can potentially change this situation, providing new priorities for ecology and conservation biology (Day et al. 2009). Whereas the modern environmental movement has emphasized coordinated, large-scale conservation activities, under a resource-constrained regime these efforts likely will give way to local, sustainability centered attitudes, which currently are most common in economically poor countries (Roe & Elliott 2005; Kareiva & Marvier 2007). This transition also can be observed and explained from a strictly financial viewpoint: the (already ongoing) financial turmoil, caused in part by global energy problems and consequent price fluctuations, is reducing availability of resources for conservation activities.

Assessing the Future

Global petroleum production is close to peak, and there are no easily accessed alternative energy sources. Even though uncertainty as to the effects of peak oil is great, the degree of threat peak oil poses to the world's societies demands urgent action (Hirsch et al. 2005). It appears to us that the impact of peak oil will be far more immediate, certain, and perhaps larger than that of climate change, although peak oil has received far less scientific scrutiny, press, and funding than climate change. Scientists are expected to help resolve the uncertainties surrounding peak oil so that farsighted policies that address the problem can be developed. Scientific models generally examine the response of specific systems with respect to changes in some external drivers. Such drivers ideally should be represented by scenarios that contain the range of major uncertainties.

Despite accumulating evidence of a growing energy crisis, the scientific community is not addressing the issue sufficiently. Rising concerns about the future of biodiversity and the continuous flow of ecosystem services can best be addressed through integrated analysis of the Earth–biosphere–society system, and this analysis should be based on complex scenarios that combine qualitative storylines with quantitative simulation over a wide range of potential futures (Alcamo 2001; Clark et al. 2001). During the last few decades, scenario-based studies have become commonplace at a variety of spatial scales. Nevertheless, most such studies use only a handful of basic scenarios that tend to be complex, sophisticated, story-and-simulation types, often elaborated by large international academic groups such as the Global Scenario Group (Raskin et al. 2002), the Intergovernmental Panel on Climate Change (IPCC) (Nakicenovic et al. 2000), and the Millennium Ecosystem Assessment (MEA) (MEA 2005). Unfortunately, due to the widely held belief throughout the 1990s that technology would continue to prevent serious resource constraints (e.g., Rogner 1997), a notion promoted by economists and adopted by many governments, most scenario-based studies consider the risk of involuntary decrease in global energy consumption to be negligible in the foreseeable future (Aleklett 2007). This hidden "resource optimism" can be recognized clearly in the IPCC SRES (Special Report on Emission Scenarios) scenarios, (Fig. 3) (Nakicenovic et al. 2000), which are the standard set of scenarios used in all relevant climate-impact studies. Supply tensions are probable from the point when half of the ultimately available quantity is consumed ("peaking zone"; Fig. 3). Even the minimum estimate for petroleum consumption is well above this amount in all IPCC SRES scenarios (Fig. 3). These scenarios fail to account for the finite nature of oil and other fossil fuels. All the 40 primary IPCC SRES simulations are based on 36–120 ZJ (1 ZJ = 10^{21} J) of cumulative fossil energy consumption during the rest of the 21st century (Nakicenovic et al. 2000), whereas, even according to the "relatively optimistic" (EWG 2007) official reserve estimates, there is no more than 31.7 ZJ of fossil energy remaining in the ground including oil, natural gas, and coal (BP 2008). The IPCC SRES scenarios (and all subsequent global, regional, and national impact assessments derived from them) seem to assume no fossil-fuel limitation during the 21st century. In light of the geologic, physical, and socioeconomic limitations of resource extraction, this unquestioned optimism of the IPCC seems to be no more than "wishful thinking" (Laherrere 2002).

The issue of peak oil is inextricably intertwined with a variety of other global environmental and social problems (e.g., climate change, intergenerational inequity, economic stability). Sharing the same major driver of fossil-energy consumption, climate change is particularly strongly linked to peak oil. Accordingly, we argue that it is necessary to develop complex, integrated story-and-simulation scenarios that represent the impacts of both climate change and peak oil. The first steps in this direction are being taken. For example, a comprehensive set of plausible storylines reflecting key uncertainties of climate and energy depletion has been constructed by Holmgren (2008), and the process of adapting the IPCC emission scenarios to recent knowledge of resource limitations has begun (Brecha 2008; Kharecha & Hansen, 2008). Ideally, a set of plausible and sophisticated story-and-simulation world scenarios are needed that include aspects of both of the most important challenges of our age (Bardi 2009). This is an immense but urgent task, which perhaps only can be coordinated by an international scientific body

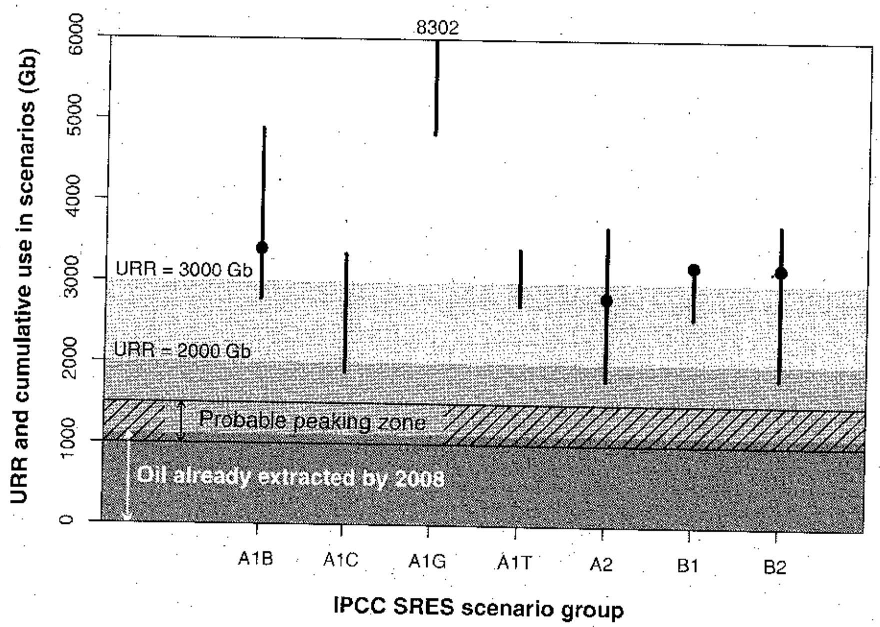

Figure 3. Cumulative global oil use from start of the industrial era (1850) until 2100 according to the Special Report on Emissions Scenarios of the Intergovernmental Panel on Climate Change (IPCC) (vertical lines, intervals of the model runs; dots, marker scenarios [illustrative scenarios for the four major scenario families]; Nakicenovic et al. 2000); quantity of oil already extracted by the start of 2008; and different estimates of the world's total ultimately recoverable reserves (URR). From 2000 to 3000 Gb (billion barrels) URR is the range of all recent (made after the year 2000) physical model-based URR estimations for either conventional oil or all liquids (including nonconventional oil and natural gas liquids) (Bentley & Boyle 2008). "Cheap oil" is only available below the hatched area (peaking oil-production zone, at half of the URR estimates). Fulfillment of any of the IPCC scenarios requires much more oil than is readily available.

of high recognition, similar to the IPCC, the MEA Board, or the IIASA (International Institute for Applied Systems Analysis), which coordinated development of the SRES scenarios. Without these fundamental efforts the usefulness of any impact, adaptation, or vulnerability study at any scale is questionable. Failing to take energy scarcity into account is like preparing for the wrong exam, with the expected negative results.

Perhaps at this point there is no politically viable solution to peak oil, just as there appears to be no politically viable solution to global climate change. Addressing the fossil-fuel issue demands reduced energy consumption, which is contrary to the political goal of economic growth. Without a comprehensive assessment of world energy supply and demand, as well as public discussion of limits to growth, it seems certain the near-term future will be filled with political rhetoric and international conflict rather than honest dialog and transparent governance.

Conclusions

Limited availability of fossil fuels likely will have huge effects on social and economic systems, no matter when the actual peak arrives. Because human activities strongly influence global ecological changes, social regime shifts definitely will induce ecological changes. On the other hand, these changes may impose detrimental feedbacks on human society, gradually depriving civilization of energy sources by "robbing" humans of the historically continuous influx of fossil fuels. The past two centuries of industrial growth have been the fossil-fuel age and witnessed human population growth, ecological changes, and human-lifestyle changes unprecedented in 10 millennia of civilization. Our present civilization has built complex systems that cannot survive without "energy subsidies" from the abundant, cheap fossil fuels, so the implications of reduced oil availability are large and difficult to contemplate. Ecologists are well positioned to provide essential analysis and expertise that can assist society in making the transition to the postpetroleum world.

An important function for ecologists and conservation biologists in a declining fossil-fuel world is to study and call attention to the types of human actions that will cause fundamental damage to ecological systems. Sounding the alarm and taking action are consistent with past and continuing efforts of applied ecologists, but much current concern is devoted to coping with the externalities of excessive use of fossil fuels (e.g., climate change, environmental damage from fossil-fuel extraction, societies dependent on economic growth), whereas the post-peak shift will necessitate social adaptation to reduced energy consumption, driving humans to compensate in ways that typically have been studied in developing societies. Preparing for an energy-scarce future necessitates allowing for energy-depletion scenarios in a wide range of future-oriented studies, including climate- or land-use-change impact assessments and strategic conservation planning (Clark et al. 2001). In view of the large body of supporting evidence, and significance of potential consequences, the ramifications of peak oil should be considered serious enough to be pursued with considerable time and resources. Inclusion of peak-oil scenarios in integrated global and regional vulnerability assessments and impact studies will allow the study of peak oil to move beyond the general qualitative statements of Table 1 toward quantitative, more detailed, nuanced, and policy-oriented assessments.

The rise of modern western civilization is not merely a product of human ingenuity and free-market principles. An often neglected but crucial factor in this process was the immense flow of fossil energy, which provided humans with significant competitive advantages over other organisms. In other words, humans found a tremendously profitable energy niche within the ecological system of the planet. But what will happen if this niche closes up? We argue that this will be the greatest social and environmental challenge of the 21st century, and both theoretical and applied ecologists will have significant roles and responsibilities in understanding and managing the transition process from today's oil-addicted growth economy focused on dominating nature to a smaller, more cooperative, and more sustainable world economy.

Acknowledgments

We thank C. A. S. Hall and two anonymous reviewers for their valuable comments to an earlier version of this manuscript.

Literature Cited

Alcamo, J. 2001. Scenarios as tools for international environmental assessment, Environmental issue report. European Environment Agency, Copenhagen.

Aleklett, K. 2007. Reserve driven forecasts for oil, gas and coal and limits in carbon dioxide emissions: peak oil, peak gas, peak coal and peak CO_2. JTRC discussion paper 2007-18. International Transport Forum/Organisation for Economic Co-operation and Development(OECD), Paris. Available from http://www.internationaltransportforum.org/jtrc/DiscussionPapers/DiscussionPaper18.pdf (accessed August 2008).

Aleklett K., and C. J. Campbell. 2003. The peak and decline of world oil and gas production. Minerals and Energy **18:**5-20.

Bardi, U. 2009. Mission Earth. The Oil Drum, 12 February. Available from http://europe.theoildrum.com/node/5043 (accessed February 2009).

Bentley, R., and G. Boyle. 2008. Global oil production: forecasts and methodologies. Environment and Planning B: Planning and Design **35:**609-626.

Boltzmann, L. 1974. The second law of thermodynamics. Pages 13-32 in B. Guiness, editor. Theoretical physics and philosophical problems. Reider Publishing, Dordrecht, The Netherlands. (Original work published 1886.)

BP (British Petroleum). 2008. Statistical review of world energy June 2008. BP, London. Available from http://www.bp.com/statisticalreview (accessed January 2009).

Brecha, R. J. 2008. Emission scenarios in the face of fossil-fuel peaking. Energy Policy **36:**3492-3504.

Cai, T. T., C. L. Montague, and J. S. Davis. 2006. The maximum power principle: an empirical investigation. Ecological Modelling **190:**317-335.

Campbell, C. J. 2005. The end of the first half of the age of oil. IV international workshop on oil and gas depletion. Geophysics Centre of Évora, University of Évora, Évora, Portugal. Available from http://www.cge.uevora.pt/aspo2005/abstracts.php (accessed January 2009).

Campbell, C. J., and J. H. Laherrere. 1998. The end of cheap oil. Scientific American **278:**60-65.

Catton, W. 1980. Overshoot: the ecological basis of revolutionary change. University of Illinois Press, Champaign, Illinois.

Clark, J. S., et al. 2001. Ecological forecasts: an emerging imperative. Science **293:**657-660.

Cleveland, C. J. 2005. Net energy from the extraction of oil and gas in the United States. Energy **30:**769-782.

Cleveland, C. J., R. Costanza, C. A. S. Hall, and R. Kaufmann. 1984. Energy and the U.S. economy: a biophysical perspective. Science **225:**890-897.

Cleveland, C. J., C. A. S. Hall, and R. A. Herendeen. 2006. Energy returns on ethanol production. Science **312:**1746-1748.

Costanza, R. 1980. Embodied energy and economic valuation. Science **210:**1219-1224.

Costanza, R., and H. Daly. 1992. Natural capital and sustainable development. Conservation Biology **6:**37-46.

Day, J. W., C. A. S. Hall, A. Yanez-Arancibia, D. Pimentel, C. I. Marti, and W. J. Mitsch. 2009. Ecology in times of scarcity. Bio Science **59:**321-331.

Deffeyes, K. 2005. Beyond oil: the view from Hubbert's peak. Hill and Wang, New York.

Duncan, R. C. 2001. World energy production, population growth, and the road to the Olduvai Gorge. Population & Environment **22:**503-522.

Ehrenfeld, D. 2005. The environmental limits to globalization. Conservation Biology **19:**318-326.

EIA (Energy Information Administration). 2008*a*. Annual energy review 2007. Table 5.1 in Petroleum Overview, 1949-2007. EIA, Washington, D.C. Available from http://www.eia.doe.gov/emeu/aer/txt/ptb0501.html (accessed January 2009).

EIA (Energy Information Administration). 2008*b*. International energy outlook 2008. Appendix G: projections of petroleum and other liquids production in five cases. EIA, Washington, D.C. Available from http://www.eia.doe.gov/oiaf/ieo/pdf/ieopol.pdf (accessed August 2008).

EWG (Energy Watch Group). 2006. Uranium resources and nuclear energy. Series no. 1/2006. EWG, Berlin. Available from http://www.energywatchgroup.org/fileadmin/global/pdf/ EWG_Report_Uranium_3-12-2006ms.pdf (accessed February 2009).

EWG (Energy Watch Group). 2007. Coal: resources and future production. Series no. 1/2007. EWG, Berlin. Available from http://www.energywatchgroup.org/fileadmin/global/pdf/ EWG_Report_Coal_10-07-2007ms.pdf (accessed February 2009).

Funtowicz, S. O., and J. R. Ravetz. 1993. Science for the post-normal age. Futures **25:**739-755.

Gagnon, N., C. Hall, and L. Brinker. 2009. A preliminary investigation of energy return on energy investment for global oil and gas production. Energies 2:490–503.

Georgescu-Roegen, N. 1971. The entropy law and the economic process. Harvard University Press, Cambridge, Massachusetts.

Giannantoni, C. 2002. The maximum em-power principle as the basis for thermodynamics of quality. Servizi Grafici Editoriali, Padova, Italy.

Goldstein, H., and W. Sweet. 2007. Joules, BTUs, quads—let's call the whole thing off. IEEE Spectrum **44**:16.

Hall, C. A. S. 1972. Migration and metabolism in a temperate stream ecosystem. Ecology **53**:585–604.

Hall, C. A. S., S. Balogh, and D. J. Murphy. 2009. What is the minimum EROI that a sustainable society must have? Energies **2**:25–47.

Hall, C. A. S., C. J. Cleveland, and R. Kaufmann. 1986. Energy and resource quality: the ecology of the economic process. Wiley-InterScience, New York.

Hall, C. A. S., and J. W. Day. 2009. Revisiting the limits to growth after peak oil. American Scientist **97**:230–237.

Hall, C. A. S., R. Powers, and W. Schoenberg. 2008. Peak oil, EROI, investments and the economy in an uncertain future. Pages 109–132. in D. Pimentel, editor. Biofuels, solar and wind as renewable energy systems. Springer, Dordrecht, The Netherlands.

Hall, C. A. S., P. Tharakan, J. Hallock, C. Cleveland, and M. Jefferson. 2003. Hydrocarbons and the evolution of human culture. Nature **426**:318–322.

Hamilton, J. D. 2009. Causes and consequences of the oil shock of 2007–08. Brookings Papers on Economic Activity, Spring 2009: 215–261.

Hau, J. L., and B. R. Bakshi. 2004. Expanding exergy analysis to account for ecosystem products and services. Environmental Science and Technology **38**:3768–3777.

Heinberg, R. 2003. The party's over: oil, war and the fate of industrial societies. New Society Publishers, Gabriola Island, British Columbia.

Hirsch, R. L. 2008. Mitigation of maximum world oil production: shortage scenarios. Energy Policy **36**:881–889.

Hirsch, R. L., R. Bezdek, and R. Wendling. 2005. Peaking of world oil production: impacts, mitigation and risk management. Report to National Energy Technology Laboratory, US Dept. of Energy. Science Applications International, San Diego, California. Available from http://www.netl.doe.gov/publications/others/pdf/Oil_Peaking_NETL.pdf (accessed August 2008).

Holmgren, D. 2008. Future scenarios—mapping the cultural implications of peak oil and climate change. Holmgren Design Services, Hepburn Springs, Victoria. Available from http://www.futurescenarios.org (accessed August 2008).

Hubbert, M. K. 1956. Nuclear energy and the fossil fuels. Publication 95. Shell Development, Houston. Available from http://www.energybulletin.net/node/13630 (accessed January 2008).

IEA (International Energy Agency). 2007. Key world energy statistics 2007. IEA, Washington, D.C. Available from www.iea.org/textbase/nppdf/free/2007/key_stats_2007.pdf (accessed August 2008).

Kareiva, P., and M. Marvier. 2007. Conservation for the people. Scientific American **297**:50–57.

Kharecha, P. A., and J. E. Hansen. 2008. Implications of "peak oil" for atmospheric CO_2 and climate. Global Biogeochemical Cycles **22** DOI: 10.1029/2007GB003142.

Laherrere, J. 2002. Forecasting future production from past discovery. International Journal of Global Energy Issues **18**:218–238.

Liu, Z., J. Koerwer, J. Nemoto, and H. Imura. 2008. Physical energy cost serves as the "invisible hand" governing economic valuation: direct evidence from biogeochemical data and the US metal market. Ecological Economics **67**:104–108.

Lotka, A. J. 1922. Contribution to the energetics of evolution. Proceedings of the National Academy of Science of the U.S.A. **8**:147–151.

MEA (Millennium Ecosystem Assessment). 2005. Ecosystems and human well-being: synthesis. Millennium Ecosystem Assessment. 1st edition. Island Press, Washington, D.C.

Meadows, D. H, D. L. Meadows, and J. Randers. 2004. Limits to growth: the 30-year global update. Chelsea Green Publishing, White River Junction, Vermont.

Meadows, D. H, D. L. Meadows, J. Randers, and W. W. Behrens. 1972. The limits to growth. Potomac Associates, Washington, D.C.

Nakicenovic, N., et al. 2000. Special report on emissions scenarios: a special report of Working Group III of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom.

Nikiforuk, A. 2008. Tar sands: dirty oil and the future of a continent. Greystone Books, Toronto, Ontario.

Odum, H. T. 1973. Energy, ecology, and economics. Ambio **2**:220–227.

Odum, H. T. 1996. Environmental accounting: EMERGY and environmental decision making. John Wiley and Sons, New York.

Odum, E. P., and G. W. Barrett. 2005. Fundamentals of ecology. 5th edition. Brooks/Cole, Belmont, California.

Odum, H. T., and E. C. Odum. 2001. A prosperous way down: principles and policies. University Press of Colorado, Boulder, Colorado.

Odum, H. T., and E. C. Odum. 2006. The prosperous way down. Energy **31**:21–32.

Pimentel, D., A. Marklein, M. A. Toth, M. Karpoff, G. S. Paul, R. McCormack, J. Kyriazis, and T. Krueger. 2008. Biofuel impacts on world food supply: use of fossil fuel, land and water resources. Energies **1**:41–78.

Pfeiffer, D. A. 2006. Eating fossil fuels: oil, food and the coming crisis in agriculture. New Society Publishers, Gabriola Island, British Columbia.

Price, D. 1999. Carrying capacity reconsidered. Population & Environment **21**:5–26.

Raskin, P., T. Banuri, G. Gallopin, P. Gutman, A. Hammond, R. Kates, R. Swart. 2002. Great transition—the promise and lure of the times ahead. Stockholm Environment Institute, Boston.

Rockstrom, J. et al. 2009. A safe operating space for humanity. Nature **461**:472–475.

Roe, D., and J. Elliott. 2005. Poverty-conservation linkages: a conceptual framework. International Institute for Environment and Development, London. Available from www.povertyandconservation.info/docs/20051I-Conceptual_Framework(Roe-Elliott).pdf (accessed January 2009).

Rogner, H. H. 1997. An assessment of world hydrocarbon resources. Annual Review of Energy and the Environment **22**:217–262.

Salameh, M. G. 2003. Can renewable and unconventional energy sources bridge the global energy gap in the 21st century? Applied Energy **75**:33–42.

Simon, J. L. 1996. The ultimate resource 2. Princeton University Press, Princeton, New Jersey.

Wackernagel, M., N. B. Schulz, D. Deumling, A. C. Linares, M. Jenkins, V. Kapos, C. Monfreda, J. Loh, N. Myers, and R. Norgaard. 2002. Tracking the ecological overshoot of the human economy. Proceedings of the National Academy of Sciences of the U.S.A. **99**:9266–9271.

WWI (World Watch Institute). 2005. State of the world 2005: redefining global security. Norton, New York.

Youngquist, W. 1999. The postpetroleum paradigm—and population. Population and Environment **20**:297–315.