

# BURNING BURIED SUNSHINE: HUMAN CONSUMPTION OF ANCIENT SOLAR ENERGY

JEFFREY S. DUKES\*

*Department of Biology, University of Utah, 257 South 1400 East, Salt Lake City,  
UT 84112-0840, U.S.A.*

*E-mail: dukes@globalecology.stanford.edu*

**Abstract.** Fossil fuels developed from ancient deposits of organic material, and thus can be thought of as a vast store of solar energy from which society meets >80% of its current energy needs. Here, using published biological, geochemical, and industrial data, I estimate the amount of photosynthetically fixed and stored carbon that was required to form the coal, oil, and gas that we are burning today. Today's average U.S. Gallon (3.8 L) of gasoline required approximately 90 metric tons of ancient plant matter as precursor material. The fossil fuels burned in 1997 were created from organic matter containing  $44 \times 10^{18}$  g C, which is >400 times the net primary productivity (NPP) of the planet's current biota. As stores of ancient solar energy decline, humans are likely to use an increasing share of modern solar resources. I conservatively estimate that replacing the energy humans derive from fossil fuels with energy from modern biomass would require 22% of terrestrial NPP, increasing the human appropriation of this resource by ~50%.

## 1. Introduction

Fossil fuel consumption is widely recognized as unsustainable. However, there has been no attempt to calculate the amount of energy that was required to generate fossil fuels (one way to quantify the 'unsustainability' of societal energy use), and discussion about the consequences of replacing fossil fuels with modern solar energy has been limited (but see Cook et al., 1991; Hall et al., 1991; Giampietro et al., 1997). Recent attempts to estimate the sustainability of human activities have taken a variety of approaches. Some researchers have estimated the amount of photosynthetic energy (in the form of NPP) that is appropriated by humans (Vitousek et al., 1986; Rojstaczer et al., 2001). Others have estimated the 'ecological footprint' of humanity, the amount of biologically productive space necessary to sustain human consumption (Wackernagel et al., 2002). Neither of these approaches takes into account the sustainability of fossil fuel consumption. The NPP approach focuses entirely on consumption and reduction of the potential photosynthetic energy captured in modern times, ignoring energy acquired through fossil fuel consumption. The ecological footprint approach usually accounts for fossil fuel burning by designating land for use in climate stabilization. This land would

\* Now at: Carnegie Institution of Washington, Department of Global Ecology, 260 Panama St., Stanford, CA, 94305-1297, U.S.A.



theoretically prevent greenhouse gas buildup by recapturing fossil fuel carbon that has entered the atmosphere (Wackernagel et al., 1999; Ferng, 2002). While this approach compensates for the climate effects of fossil fuel burning, it does not replenish the original store of energy. Rarely, footprint analyses account for fossil energy use by calculating the amount of land required to grow biomass or biofuels that could act as energy substitutes for fossil fuels. This replacement approach often leads to larger footprints than the climate stabilization approach (Wackernagel et al., 2002). True analyses of sustainability must take into account the land or NPP needed to replace the stored energy that we use.

Here, I have compiled data on: (1) the proportion of fossil fuel reserves derived from different environments (i.e., terrestrial vs. marine vs. lacustrine), (2) the efficiency with which photosynthetic organisms are converted to peat or carbon-rich sediment in these environments, (3) the efficiency with which organic deposits were converted to fossil fuels, and (4) the efficiency with which we are able to retrieve fossil fuels from near the earth's surface. From these data, I calculate the amount of paleoproductivity that was needed to create fossil fuels. I also estimate the amount of solar energy consumed by humans in the form of fossil fuels, compare the solar efficiency of fossil fuels to that of more modern sources of solar-derived energy, and estimate the minimum amount of modern photosynthetic product necessary to replace fossil fuel energy.

## 2. Methods

In this paper, a preservation factor (PF) is defined as the fraction of carbon that remains at the end of a transition from one fossil fuel precursor to the next, such as that from plant matter to peat, on the path to coal formation. A recovery factor (RF) is defined as the proportion of original photosynthetic product recovered as fossil fuel. Recovery factors are the product of the PFs of each transition and additional terms for extraction efficiency (for instance, the fraction of existing coal that can be mined from deposits given today's economic and technological setting). In some cases, a fossil fuel has been generated in a variety of environments or through multiple pathways. In these cases, PFs or efficiency values were determined for each of the conditions, and the relevant PF was applied to the fraction of fossil fuel that was generated in each condition. In this manner, RFs are estimated for the global pools of coal, oil, and gas. RFs of individual fossil fuel deposits undoubtedly range widely around these estimates. Where appropriate, I determined high and low limits and an intermediate best estimate for the efficiency values involved in the calculation of recovery factors. Limits were generally determined by taking the most extreme values reported in the literature, with some constraint on these values due to biological, physical or logical considerations (for instance, conversion efficiencies are greater than zero). It is possible that many deposits of a given fossil fuel type experienced the high (or low) PF limit during one transition. However,

it is unlikely that a large fraction of modern fossil fuel reserves experienced the highest (or lowest) PF limits through all transitions. Therefore, RF limits are very likely to encompass the global RF for each fuel type.

### 3. Recovery of NPP as Coal

Much of Earth's coal (often termed 'buried sunshine' by the coal industry) is thought to have accumulated in environments analogous to the peat swamp forests of Indonesia and Malaysia (Moore, 1987; Moore, 1989; Cobb and Cecil, 1993). The calculations in this study assume that coal formed entirely from ombrogenous (precipitation-dependent) peat deposits such as these. Neuzil (1997) determined carbon accumulation rates in 2000–10,000 year old Indonesian domed peat deposits. Average rates for four sites ranged from 61–145 g C m<sup>-2</sup> yr<sup>-1</sup> (the mean across these sites is 105 g C m<sup>-2</sup> yr<sup>-1</sup>). These rates are comparable to or higher than other values for the region (I derived rates between 2 and 190 g C m<sup>-2</sup> yr<sup>-1</sup> from data in Cameron et al. (1989) and Supardi et al. (1993)). Comprehensive NPP measurements of these forests have not been completed (J. O. Rieley, pers. comm.). I used data published by Brady (1997) to estimate the productivity of forests on three raised peat deposits in Sumatra, Indonesia. On an annual basis, litter and new roots in the lower half of the acrotelm (the topmost, aerobic peat layer) added 310–678 g C m<sup>-2</sup> yr<sup>-1</sup> to the peat (mean = 436 g C m<sup>-2</sup> yr<sup>-1</sup>). Root production in the top half of the acrotelm was not measured. To estimate this value, I multiplied root ingrowth in the lower half of the acrotelm by the ratio of dry root mass in the upper half to dry root mass in the lower half. If this estimate is included, then 373–1456 g C m<sup>-2</sup> (mean = 672) enters the peat annually. Dividing the mean estimate of annual C accumulation by the mean estimate for annual C input gives an estimate of  $105 \div 672 = 15.6\%$  for the PF of organic carbon in peat, with a low limit of  $61 \div 1456 = 4\%$  and a high limit of  $145 \div 373 = 39\%$ . This estimate nearly matches the 15% of NPP that Moore (1987) calculated remains as peat in British blanket mires.

With time, heat, and pressure, peat undergoes coalification. During this process, the water content declines and the carbon concentration increases. The peat is gradually transformed to brown coal (lignite and sub-bituminous), and finally to hard coal (bituminous and anthracite; Taylor et al., 1998). Meanwhile, some carbon is lost as volatile CO, CO<sub>2</sub>, and CH<sub>4</sub> (Kopp et al., 2000). Peat retains approximately 92.5% of its C as it is converted to high-volatile bituminous coal (see Table I). Between 68% and 84% of the C present in high-volatile bituminous coal is retained as the coal increases in rank to anthracite (Table II). The PFs of brown coal and hard coal are approximately 95.5% (limits: 92.5% and 98.5%), and 69% (limits: 63% and 78%; estimate derived from a 92.5% PF for high-volatile bituminous followed by a 75% PF during further increases in rank), respectively.

Table I  
Carbon retained during early coalification transitions. Based on Mott (1942, 1943)

Rank transition	% C	Reaction products lost	%wt. Loss/ %C increase	%C retained
Peat-lignite	57–65	62H <sub>2</sub> O + 9CH <sub>4</sub> or	1.77	98.79–
		64H <sub>2</sub> O + 8CH <sub>4</sub> + CO <sub>2</sub>		98.84
Lignite-low rank bituminous	65–77	CO <sub>2</sub>	1.93	93.68

Table II  
Carbon retained in coal during late coalification

Rank transition	Number of C atoms lost <sup>a</sup>	% initial C remaining after transition
Beginning to end of high-volatile bituminous	129–1544	98.71–84.56
Beginning of medium-volatile bituminous to end of low-volatile bituminous	318–519	95.57–80.17
Beginning to end of semi-anthracite	389–574	91.85–75.57
Beginning to end of anthracite	816–985	84.36–68.13

<sup>a</sup> Per 10,000 C atoms at beginning of transition (Kopp and Bennett, 2001).

Recently, world reserves were estimated to consist of 48% brown coal and 52% hard coal (Trinnaman and Clarke, 1998). Assuming that 50% of the original world coal reserve was of high-volatile bituminous or lower rank gives a global mean PF in the transition from plant matter to coal of 13% (peat PF of 15.6% multiplied by 95.5% for brown coal or 69% for hard coal; the average of these products is 13%).

Coal deposits are only partially removed from mines. On average, 62% of underground deposits and 82% of surface deposits are extractable using current mining techniques (Arioglu, 1994). Because almost two thirds of world hard coal production comes from underground mines (World Coal Institute, 2000), the global coal extraction PF is roughly 69%.

Using the PF values listed above, I calculated the mean global recovery factor for coal (Figure 1). In addition, I used only the low PF limits to calculate a low RF limit, and only the highest PF limits to calculate a high RF limit. The global recovery factor for coal is 0.09, and RF limits are 0.02 and 0.2.

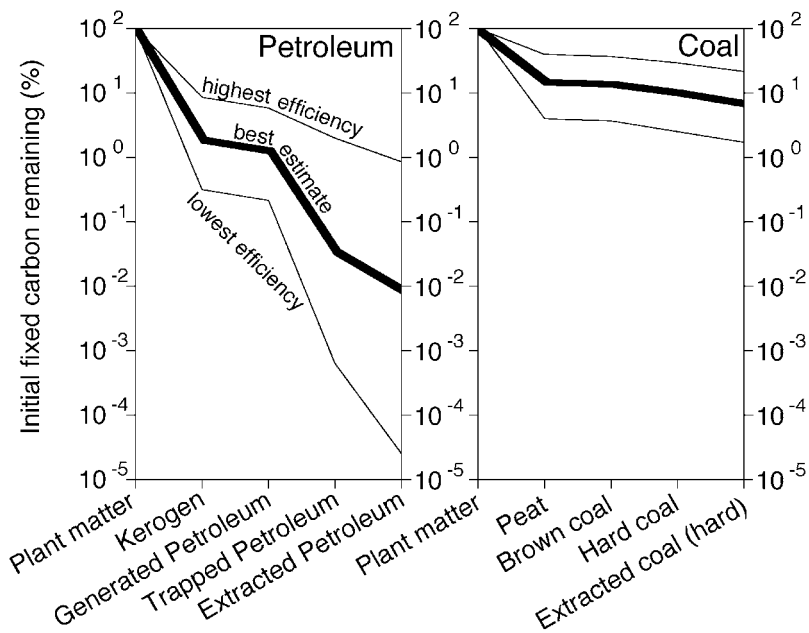


Figure 1. Best estimate (thick line) and high and low limits (thin lines) for the percent of photosynthetically fixed carbon retained during fuel generation and extraction. The final value in each panel is the equivalent of a recovery factor (RF) for the fuel type. The actual RF for coal varies slightly from the value in the figure, because both brown coal and hard coal are extracted from the earth.

#### 4. Recovery of NPP as Petroleum

Marine sediments produced the majority (about 86%) of the world's petroleum, while deltaic and lacustrine sediments yielded smaller amounts (about 11% and 3%, respectively) (Demaison, 1993). The organic matter in carbon-rich marine sediments is primarily composed of the remains of phytoplankton. The percentage of annually fixed organic carbon that accumulates in sediment (the PF) is difficult to estimate because it can vary over several orders of magnitude, depending on the length of time that organic matter experiences oxic conditions, and on other factors (Bralower and Thierstein, 1987; Bordenave, 1993; Canfield, 1994; Gélinas et al., 2001). Two types of marine settings are thought to have been the major environments for the formation of petroleum source rocks: silled basins with oxygen-deficient waters, and highly productive upwelling zones (which generated 78% and 8% of world petroleum stocks, respectively; Demaison, 1993).

In modern anoxic basins, PFs are generally between 0.5% and 10% (Bralower and Thierstein, 1987). In highly productive coastal upwelling zones, PFs can range from 1–10% (Lückge et al., 1996). In both cases, preservation factors at the lower end of the range are more typical. I used a best estimate of 2% for the PF in both settings. I used 9.3% as the high limit for preservation of fixed carbon in sediments of anoxic silled basins. This fraction is equal to the highest PF calculated for the

Black Sea (9.3%) (Bralower and Thierstein, 1987), which is one of the best modern examples of this type of setting (Bordenave, 1993). In upwelling zones, I used a high PF limit of 4.25%, which is equal to the highest PF in an area of upwelling (Site 723) off the coast of Oman, assuming NPP of  $200 \text{ g C m}^{-2} \text{ yr}^{-1}$  (Lückge et al., 1996). In both environments, I used 0.32% as a low limit. This value is the global average PF for organic carbon in marine settings (Hedges and Keil, 1995).

As in marine environments, PFs in lacustrine environments depend largely on the length of time that the sediment is exposed to oxidation in the water column. Anoxic lakes were good environments for petroleum source rock formation because mineralization of photosynthetically fixed carbon was limited. I used the same PF values for lacustrine environments as for anoxic silled marine basins, on the assumption that the behavior of organic material in these environments would be similar.

Terrestrial plant material makes up a large fraction of most deltaic sediments that have produced petroleum (Taylor et al., 1998). I found no published values for PFs in deltaic sediments with the potential for petroleum generation. I used the same PF values for organic matter in these sediments as for organic matter in upwelling zones.

Kerogen is the complex, polymeric organic matter in sediments. With time, heat, and pressure, some types of kerogen generate petroleum. Kerogens of type I, II, and III are the most common sources of fossil fuels. These kerogen types differ in their origin, their requirements for the release of hydrocarbons, and the amount and type of hydrocarbons released. Kerogens of type I and II are typically derived from lacustrine algae and marine phytoplankton, respectively (Tissot and Welte, 1984). Type III kerogens are largely derived from terrestrial plant matter.

The 'genetic potential' of kerogen describes the maximum fraction of organic matter that can be released from a kerogen as petroleum over the course of maturation (the remaining carbon is essentially inert). Kerogen types vary in their genetic potential. Types I and II have high genetic potentials (0.895 and 0.695, respectively) compared to type III (0.313) (Tissot and Welte, 1984). Kerogens of types I and II generate significant quantities of oil and gas. Type III kerogen mainly releases hydrocarbons as gas, but releases less gas per unit carbon than kerogen of types I and II (Peters and Cassa, 1994).

For this study, petroleum reservoirs derived from lacustrine, marine, and deltaic sediments were assumed to have been generated entirely from kerogen of types I, II, and III, respectively. I applied the genetic potential of each kerogen type to the corresponding fraction of global petroleum reserves to estimate the efficiency of petroleum release from organic matter stored in kerogens.

Of the petroleum generated from type I or II kerogens, approximately 76% is oil and 24% is gas (by carbon content). Of the petroleum generated by type III kerogens or coal, 59% is gas and 41% is oil (petroleum-generating coal is treated as a type III kerogen for the purposes of this estimate) (Klemme and Ulmishek, 1991).

Not all hydrocarbons that are generated migrate from the source rock to a reservoir from which they may be recovered. A substantial fraction may remain at the site of generation (Vandenbroucke, 1993) or may flow into geological features from which it is not recoverable or from which it can escape to the surface (Magoon and Valin, 1994). The percentage of generated petroleum that accumulates in reservoirs varies widely among petroleum systems (0.3–36.3% in a survey of 16 systems; Magoon and Valin, 1994). I used a weighted average (2.8%) calculated from the petroleum systems surveyed by Magoon and Valin (1994) as a best estimate. Even when oil migrates to a suitable reservoir, it is only partially recoverable, with the extractable fraction depending on the nature of the reservoir. For instance, a greater percentage of oil is generally recovered from sands (30% or more) than from carbonate reservoirs (typically 10–20%) (Selley, 1998). Extraction percentages varied from 0–83% across the 16 systems surveyed by Magoon and Valin (1994); I used the weighted average for these systems (24.5%) as a best estimate, and I used the second-lowest (4.1%) and second-highest (43.1%) values from these 16 systems as limits.

Using the PF values for petroleum transitions listed above and the same technique applied to coal, I calculated recovery factors for oil and gas (Figure 1). The RF for oil is  $90 \times 10^{-6}$ , with limits of  $0.3 \times 10^{-6}$  and  $9 \times 10^{-3}$ . For gas, the RF is  $80 \times 10^{-6}$ , with limits of  $0.2 \times 10^{-6}$  and  $8 \times 10^{-3}$ .

## 5. Applications of the Recovery Factors

The RFs can be used to calculate the amount of photosynthetic matter needed to produce a given amount of fuel, or to compare the solar efficiency of various electricity generating techniques (Table III).

For instance, I used the RFs to estimate the amount of ancient photosynthetic product consumed annually in the form of fossil fuels (Figure 2). Approximately 44 Eg ( $44 \times 10^{18}$  g; limits: 0.5 Eg and  $15 \times 10^3$  Eg) of photosynthetic product-carbon were necessary to generate the fossil fuels burned in 1997 (Table IV). This is equivalent to 422 times the net amount of carbon that is fixed globally each year (Field et al., 1998), or 73 times the global standing stock of carbon in vegetation (Schimel, 1995; Figure 2). Assuming that the photosynthetic process has an average efficiency of 1.7% (Potter et al., 1993) and plant matter is 45% carbon, the amount of solar energy required to grow this vegetation was  $120 \times 10^{24}$  J, or 36 times the sum of solar energy that strikes Earth's surface in one year.\* An examination of paleoproductivity use over time suggests that societal consumption of this resource has exceeded the current rate of global carbon fixation since 1888 (Figure 2). Cumulative paleoproductivity consumption from 1751 to 1998 exceeds

\* An average of  $198 \text{ W m}^{-2}$  of solar energy reaches Earth's surface (Kiehl and Trenberth, 1997). Based on Earth's mean volumetric radius of 6371 km, Earth's surface area is  $0.51 \times 10^{15} \text{ m}^2$ . Thus, Earth's surface receives approximately  $0.1 \times 10^{18} \text{ J s}^{-1}$ , or  $3.2 \times 10^{24} \text{ J yr}^{-1}$ .

Table III  
Electricity generated by 1 kJ of solar energy

Capture technology/fuel	Efficiencies <sup>a</sup>			Storage time (yrs)	J generated
	Energy capture	Fuel synthesis	Electricity generation		
Solar <sup>b</sup>	0.15	1	1	0	150
Photosynthesis/biomass	0.024	1	0.21	~1	5.0
Photosynthesis/coal	0.024	0.089	0.38	>10 <sup>7</sup>	0.81
Photosynthesis/gas	0.024	84 × 10 <sup>-6</sup>	0.42	>10 <sup>7</sup>	0.85 × 10 <sup>-3</sup>
Photosynthesis/oil	0.024	93 × 10 <sup>-6</sup>	0.42	>10 <sup>7</sup>	0.94 × 10 <sup>-3</sup>

<sup>a</sup> Monteith (1977) found that four crop species used solar energy with 2.4% efficiency. Photosynthetic efficiency of plants in natural landscapes is generally lower. Potter et al. (1993) suggest an average global efficiency of 0.39 g C MJ<sup>-1</sup> PAR, which translates to approximately 1.7% photosynthetic efficiency (assuming that half of solar radiation is in the photosynthetically active wavelengths, that plant matter is 45% C, and that the energy content of plant matter is 20 kJ g<sup>-1</sup>). The estimated efficiency of electricity generation from biomass (21%) is an intermediate value from a range of estimates of the efficiency of current commercial technologies (Larson and Marrison, 1997; Paisley and Anson, 1998). Estimates of the efficiency of electricity generation from coal, oil, and gas are based on 'heat rate' values published by the Energy Information Administration (2000). For each fuel type, values are based on the most efficient electricity generation methodology listed.

<sup>b</sup> This value is representative of both photovoltaic and solar thermal generation technologies. Data on photovoltaic panel efficiency are made available on the web by BP Solar (Linthicum, Maryland, U.S.A.; <http://www.bpsolar.com/>). Data on the efficiency of solar thermal generation technologies were obtained from the U.S. Department of Energy (1997).

1.4 × 10<sup>3</sup> Eg C (limits: 15 Eg and 0.5 × 10<sup>6</sup> Eg; Figure 2), which is more than 13,300 years' worth of global NPP.

The RF for oil suggests that 89 metric tons of ancient plant matter were required to create 1 U.S. Gallon [3.8 L] of gasoline. This calculation assumes that the specific gravity of oil is 0.86, the carbon content is 0.85, and that 1.5 kg of oil are required to produce 1 kg of gasoline.

It has long been known, as the calculations in this paper again make clear, that the rate at which humans are using our planet's reserve of stored solar energy is not sustainable. Earth receives solar energy at a relatively constant rate, and little of the incoming energy is chemically stored through photosynthesis (Larcher, 1995). Of the organic matter that is produced annually, only a small fraction is synthesized in environments that are suitable for long-term preservation.

The extent and location of fossil-fuel-generating environments has varied widely over geologic time, with changes in global climate, ocean hydrodynamics, and eustatic transgressions, and with the evolution of photosynthetic and decomposer organisms (Klemme and Ulmishek, 1991). Estimates in this paper are largely based on the behavior of modern organic matter in regions where conditions are believed



Table IV

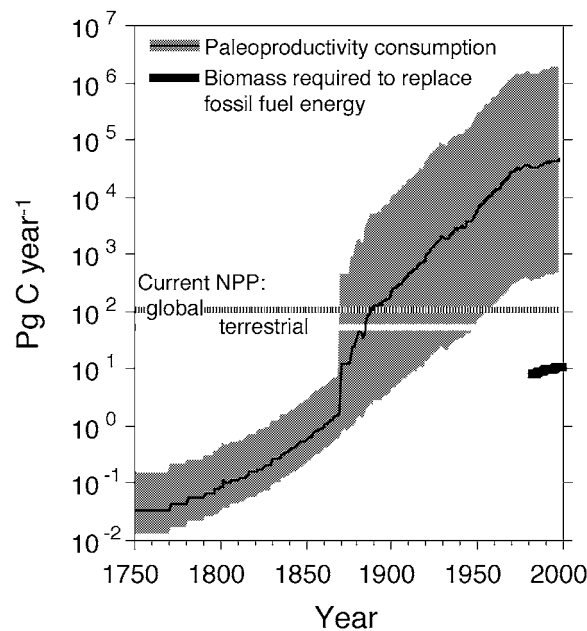
Human consumption of fossil fuels and prehistoric net primary productivity (PNPP)

Fuel type	1997 fuel consumption in Tg C <sup>a</sup>	1997 PNPP consumption in Pg C <sup>b</sup> (range)
Gas	1,210	14,252 (152–5,029,542)
Gas flaring	48	565 (6–199,519)
Liquid (oil)	2,723	29,186 (295–10,217,550)
Solid (coal)	2,437	27 (10–114)
TOTAL	6,418	44,031 (464–15,446,724)

<sup>a</sup> Teragrams ( $10^{12}$  g) of carbon; data from Marland et al. (2001).<sup>b</sup> Petagrams ( $10^{15}$  g) of carbon; best estimates and ranges calculated from recovery factors presented in text. Rounding prevents the total from equaling the sum of components.

to reasonably mimic those of ancient fossil fuel-forming environments. Although these analogous environments exist today, it is impossible to predict which, if any, modern photosynthetic products will ever generate mineable fossil fuel deposits. For this reason, the calculations here cannot be used to estimate how much modern NPP would be required to produce a given amount of fossil fuel in the future.

The RFs calculated here are estimates, with a considerable amount of associated uncertainty. Some of this uncertainty may be reduced as future studies better quantify the range of PFs in different environments. However, other sources of uncertainty are impossible to eliminate. For instance, the use of imperfect modern analogs of fossil fuel-generating environments leads to uncertainty that cannot be easily estimated or removed from PF values. Also, productivity and carbon accumulation rates undoubtedly varied from one fossil fuel-generating site to the next, and over time, and this variation introduces additional uncertainty. Possibly the greatest uncertainties are associated with variability among petroleum systems in the efficiency of petroleum generation and accumulation. Such variation makes it impossible to arrive at indisputable global estimates. However, the limits presented here almost certainly encompass global mean RFs, based on observed rates of biological and geological processes. Economic conditions and new technologies can alter RFs by a limited amount; for instance, if technological developments allow further recovery of oil from fields that are currently not economically viable, the RF for oil could increase up to fourfold.



*Figure 2.* Human consumption of paleoproductivity. The amount of ancient, photosynthetically fixed carbon that was required to generate the fossil fuels used annually between 1751 and 1998 (thin line – best estimate, grey space – area within high and low limits). Horizontal bars represent estimates for the current annual NPP (global and terrestrial) (Field et al., 1998). The thick line represents a conservative estimate of the amount of biomass that would be consumed if fossil fuel energy sources were replaced with modern biofuels. This line starts in 1980, and is calculated using data for global fossil energy consumption, which can be found in United Nations (2000) and in earlier editions of the same publication. Data for fossil fuel consumption from 1751–1998 are presented in Marland et al. (2001). The onset of oil consumption in 1870 causes the jump in the high limit and best estimate for paleoproductivity consumption. This jump is unrealistically steep because oil consumption is recorded as integer units in teragrams of carbon; in 1870 this value jumps from 0 to 1.

## 6. Replacing Ancient Energy Sources with Modern Energy Sources

Despite their solar inefficiency, fossil fuel deposits from the last ~500 million years grew large enough to supply the growing human population with ample, relatively cheap energy for the last 250 years. Fossil fuels have supported a rapid increase in energy use, while minimizing the need for widespread capture of modern solar resources. As the global stores of fossil fuels become depleted (or as climate considerations force a societal curtailment of fossil carbon releases to the atmosphere), society must either reduce energy consumption or switch to other energy sources. Replacing fossil fuel energy with modern photosynthetic energy from biomass would increase solar efficiency (as calculated in Table III), but would shift our energy demands to current NPP, which is already in demand by humans as well as other species. I calculated the amount of modern photosynthetic product that

would be required to match the energy content of the fossil fuels burned annually by humans.

I divided the 1997 global fossil energy requirement of 315271 PJ (United Nations, 2000) (this value includes only the energy content of fossil fuels, which fulfilled 83% of the total energy requirement) by a typical value for heat of combustion of wood (20 kJ/g dry biomass) to arrive at a biomass requirement of 15.8 Pg. This estimate is conservative, because wood has a higher energy content than other plant materials. Assuming biomass is 45% carbon, the fixed carbon requirement is 7.1 Pg. Roughly 44% of terrestrial NPP is stored in belowground tissues (Saugier et al., 2001) that would not be harvested for energy use, but which are considered to be co-opted upon harvest.\* If terrestrial NPP is 56.4 Pg C (Field et al., 1998), then aboveground NPP is 31.6 Pg C, suggesting society would require 22% ( $7.1 \div 31.6 = 0.22$ ) of this resource (Figure 2). This should be considered a minimum requirement; a dramatically larger share of NPP would be needed if the efficiency of energy generation from biomass remained lower than the efficiency of energy generation from fossil fuels (Table III), or if biomass were to be converted to ethanol or other liquid fuels (Giampietro et al., 1997; Kheshgi et al., 2000).

I used calculations of Vitousek et al. (1986) to estimate the degree to which replacing fossil fuel energy with energy in modern biomass would increase societal demands on NPP. Vitousek et al. (1986) calculate that on an annual basis, humans appropriate 58.1 Pg of the planet's potential terrestrial organic matter production (149.6 Pg). If modern biomass replaced fossil fuels (and unharvested root matter was counted towards consumed NPP), society would require at least an additional 28.1 Pg of organic matter per year.\*\* Thus, this simple and conservative calculation suggests that a wholesale conversion to bioenergy would increase societal demands on Earth's terrestrial photosynthetic resources by approximately 50%.

## 7. Conclusion and Implications

Ancient organic matter generated fossil fuels through inefficient processes. Calculations in this paper suggest that the formation of coal from plants is less than 10% efficient, and the formation of oil and gas from phytoplankton is less than 0.01% efficient. These estimates imply that the fossil fuels used by humans in 1997 were generated from ancient organic matter that contained approximately  $44 \times 10^{18}$  g C, which is >400 times the current global NPP. As fossil fuel stores are depleted, modern solar resources are likely to supply an increasing fraction of societal energy demands. Fortunately, these resources are more efficient than

\* In coppicing systems, where aboveground material regrows from established roots after harvests, this calculation may overestimate the NPP requirement. However, as an estimate of the fraction of current NPP that would be required, this calculation seems reasonable.

\*\* Extensive use of agricultural byproducts and residues could decrease this demand by a small amount.

fossil fuels in terms of solar energy capture (Table III). However, to the extent that a shift away from ancient solar resources increases human consumption of modern NPP, this shift could place additional burdens on the myriad species that depend on the sun's energy for life (Cook et al., 1991; Giampietro et al., 1997). By minimizing society's future energy demands and carefully selecting energy capture and generation technologies, we can limit human impacts on many other species.

### Acknowledgements

I thank O. Kopp, J. Randerson, S. Neuzil, L. Magoon, D. Bowling, J. Ehleringer, J. Fessenden, S. Schwinning, J. Verville, and three anonymous reviewers for helpful comments on earlier drafts. I am grateful to R. Dunbar, J. Harrison, R. Littke, J. Quick, W. Schlesinger, G. Telesford and many others for their help and suggestions. This research was supported by an Alexander Hollaender Distinguished Postdoctoral Fellowship, sponsored by the U.S. Department of Energy's Office of Biological and Environmental Research, and administered by the Oak Ridge Institute for Science and Education.

### References

- Arioglu, E.: 1994, 'Outlook for Coal Reserves, Production, Consumption, International Coal Trade', in Kural, O. (ed.), *Coal: Resources, Properties, Utilization, Pollution*, Istanbul Technical University, Istanbul, pp. 183–195.
- Bordenave, M. L.: 1993, 'The Sedimentation of Organic Matter', in Bordenave, M. L. (ed.), *Applied Petroleum Geochemistry*, Éditions Technip, Paris, pp. 15–76
- Brady, M. A.: 1997, 'Effects of Vegetation Changes on Organic Matter Dynamics in Three Coastal Peat Deposits in Sumatra, Indonesia', in Rieley, J. O. and Page, S. E. (eds), *Biodiversity and Sustainability of Tropical Peatlands*, Samara Publishing Limited, Cardigan, pp. 113–134
- Bralower, T. J. and Thierstein, H. R.: 1987, 'Organic Carbon and Metal Accumulation Rates in Holocene and Mid-Cretaceous Sediments: Palaeoceanographic Significance', in Brooks, J. and Fleet, A. J. (eds.), *Marine Petroleum Source Rocks*, Geological Society Special Publication No. 26, pp. 345–369.
- Cameron, C. C., Esterle, J. S., and Palmer, C. A.: 1989, 'The Geology, Botany and Chemistry of Selected Peat-Forming Environments from Temperate and Tropical Latitudes', *Int. J. Coal Geology* **12**, 105–156.
- Canfield, D. E.: 1994, 'Factors Influencing Organic Carbon Preservation in Marine Sediments', *Chem. Geol.* **114**, 315–329.
- Cobb, J. C. and Cecil, C. B. (eds.): 1993, *Modern and Ancient Coal-Forming Environments*, Geological Society of America Special Paper 286, Boulder, CO.
- Cook, J. H., Beyea, J., and Keeler, K. H.: 1991, 'Potential Impacts of Biomass Production in the United States on Biological Diversity', *Ann. Rev. Energy and the Environment* **16**, 401–431.
- Demaison, G.: 1993, 'Contributions of Geochemistry to Exploration Strategy', in Bordenave, M. L. (ed.), *Applied Petroleum Geochemistry*, Éditions Technip, Paris, pp. 489–503.
- Energy Information Administration: 2000, *Electric Power Annual 1999: Vol. II*, U.S. Department of Energy, Washington.

- Ferng, J.-J.: 2002, 'Toward a Scenario Analysis Framework for Energy Footprints', *Ecological Economics* **40**, 53–69.
- Field, C. B., Behrenfeld, M. J., Randerson, J. T., and Falkowski, P.: 1998, 'Primary Production of the Biosphere: Integrating Terrestrial and Oceanic Components', *Science* **281**, 237–240.
- Gélinas, Y., Baldock, J. A., and Hedges, J. I.: 2001, 'Organic Carbon Composition of Marine Sediments: Effect of Oxygen Exposure on Oil Generation Potential', *Science* **294**, 145–148.
- Giampietro, M., Ulgiati, S., and Pimentel, D.: 1997, 'Feasibility of Large-Scale Biofuel Production: Does an Enlargement of Scale Change the Picture?', *BioScience* **47**, 587–600.
- Hall, D. O., Mynick, H. E., and Williams, R. H.: 1991, 'Cooling the Greenhouse with Bioenergy', *Nature* **353**, 11–12.
- Hedges, J. I. and Keil, R. G.: 1995, 'Sedimentary Organic Matter Preservation: An Assessment and Speculative Synthesis', *Marine Chemistry* **49**, 81–115.
- Kheshgi, H. S., Prince, R. C., and Marland, G.: 2000, 'The Potential of Biomass Fuels in the Context of Global Climate Change: Focus on Transportation Fuels', *Ann. Rev. Energy and the Environment* **25**, 199–244.
- Kiehl, J. T. and Trenberth, K. E.: 1997, 'Earth's Annual Global Mean Energy Budget', *Bull. Amer. Meteorol. Soc.* **78**, 197–208.
- Klemme, H. D. and Ulmishek, G. F.: 1991, 'Effective Petroleum Source Rocks of the World: Stratigraphic Distribution and Controlling Depositional Factors', *The American Association of Petroleum Geologists Bulletin* **75**, 1809–1851.
- Kopp, O. C. and Bennett III, M. E.: 2001, 'A Comparison of the Loss of CO and CO<sub>2</sub> during Coalification', *Int. J. Coal Geology* **47**, 63–66.
- Kopp, O. C., Bennett III, M. E., and Clark, C. E.: 2000, 'Volatiles Lost during Coalification', *Int. J. Coal Geology* **44**, 69–84.
- Larcher, W.: 1995, *Physiological Plant Ecology: Ecophysiology and Stress Physiology of Functional Groups*, Springer-Verlag, Berlin.
- Larson, E. and Marrison, C. I.: 1997, 'Economic Scales for First-Generation Biomass-Gasifier/gas Turbine Combined Cycles Fueled from Energy Plantations', *Journal of Engineering for Gas Turbines and Power – Transactions of the American Society of Mechanical Engineers* **119**, 285–290.
- Lückge, A., Boussafir, M., Lallier-Vergés, E., and Littke, R.: 1996, 'Comparative Study of Organic Matter Preservation in Immature Sediments along the Continental Margins of Peru and Oman. Part I: Results of Petrographical and Bulk Geochemical Data', *Organic Geochemistry* **24**, 437–451.
- Magoon, L. B. and Valin, Z. C.: 1994, 'Overview of Petroleum Case Studies', in Magoon, L. B. and Dow, W. G. (eds.), *The Petroleum System – From Source to Trap: AAPG Memoir 60*, American Association of Petroleum Geologists, Tulsa, Oklahoma, pp. 329–338.
- Marland, G., Boden, T. A., and Andres, R. J.: 2001, 'Global, Regional, and National CO<sub>2</sub> Emissions', *Trends: A Compendium of Data on Global Change*, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee, U.S.A.
- Monteith, J. L.: 1977, 'Climate and the Efficiency of Crop Production in Britain', *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences* **281**, 277–284.
- Moore, P. D.: 1987, 'Ecological and Hydrological Aspects of Peat Formation', in Scott, A. C. (ed.), *Coal and Coal-Bearing Strata: Recent Advances*, Blackwell Scientific, Oxford, pp. 7–15.
- Moore, P. D.: 1989, 'The Ecology of Peat-Forming Processes: A Review', in Lyons, P. C. and Alpern, B. (eds), *Peat and Coal: Origin, Facies, and Depositional Models*, pp. 89–103.
- Mott, R. A.: 1942, 'The Origin and Composition of Coals', *Fuel in Science and Practice* **21**, 129–135.
- Mott, R. A.: 1943, 'The Origin and Composition of Coals', *Fuel in Science and Practice* **22**, 20–26.
- Neuzil, S. G.: 1997, 'Onset and Rate of Peat and Carbon Accumulation in Four Domed Ombrogenous Peat Deposits, Indonesia', in Rieley, J. O. and Page, S. E. (eds.), *Biodiversity and Sustainability of Tropical Peatlands*, Samara Publishing Limited, Cardigan, pp. 55–72.

- Paisley, M. A. and Anson, D.: 1998, 'Biomass Gasification for Gas Turbine-Based Power Generation', *Journal of Engineering for Gas Turbines and Power – Transactions of the American Society of Mechanical Engineers* **120**, 284–288.
- Peters, K. E. and Cassa, M. R.: 1994, 'Applied Source Rock Geochemistry', in Magoon, L. B. and Dow, W. G. (eds.), *The Petroleum System – From Source to Trap: AAPG Memoir 60*, American Association of Petroleum Geologists, Tulsa, Oklahoma, pp. 93–120.
- Potter, C. S., Randerson, J. T., Field, C. B., Matson, P. A., Vitousek, P. M., Mooney, H. A., and Klooster, S. A.: 1993, 'Terrestrial Ecosystem Production: A Process Model Based on Global Satellite and Surface Data', *Global Biogeochem. Cycles* **7**, 811–841.
- Rojstaczer, S., Sterling, S. M., and Moore, N. J.: 2001, 'Human Appropriation of Photosynthesis Products', *Science* **294**, 2549–2552.
- Saugier, B., Roy, J., and Mooney, H. A.: 2001, 'Estimations of Global Terrestrial Productivity: Converging towards a Single Number?', in Roy, J., Saugier, B., and Mooney, H. A. (eds.), *Terrestrial Global Productivity*, Academic Press, San Diego, CA, pp. 543–557.
- Schimel, D. S.: 1995, 'Terrestrial Ecosystems and the Carbon Cycle', *Global Change Biology* **1**, 77–91.
- Selley, R. C.: 1998, *Elements of Petroleum Geology*, Academic Press, San Diego, CA.
- Supardi, Subekty, A. D., and Neuzil, S. G.: 1993, 'General Geology and Peat Resources of the Siak Kanan and Bengkalis Island Peat Deposits, Sumatra, Indonesia', in Cobb, J. C. and Cecil, C. B. (eds.), *Modern and Ancient Coal-Forming Environments*, Geological Society of America Special Paper 286, Boulder, CO, pp. 45–61.
- Taylor, G. H., Teichmüller, M., Davis, A., Diessel, C. F. K., Littke, R., and Robert, P.: 1998, *Organic Petrology*, Gebrüder Borntraeger, Berlin.
- Tissot, B. P. and Welte, D. H.: 1984, *Petroleum Formation and Occurrence*, Springer-Verlag, Berlin.
- Trinaman, J. and Clarke, A. (eds.): 1998, *Survey of Energy Resources*, World Energy Council, London.
- U.S. Department of Energy, Office of Utility Technologies and the Electric Power Research Institute: 1997, 'Overview of Solar Thermal Technologies', *Renewable Energy Technology Characterizations*, EPRI, Palo Alto, CA, pp. 5.1–5.5.
- United Nations: 2000, *1997 Energy Statistics Yearbook*, United Nations, New York.
- Vandenbroucke, M.: 1993, 'Migration of Hydrocarbons', in Bordenave, M. L. (ed.), *Applied Petroleum Geochemistry*, Éditions Technip, Paris, pp. 123–148.
- Vitousek, P. M., Ehrlich, P. R., Ehrlich, A. H., and Matson, P. A.: 1986, 'Human Appropriation of the Products of Photosynthesis', *BioScience* **36**, 368–373.
- Wackernagel, M., Lewan, L., and Hansson, C.: 1999, 'Evaluating the Use of Natural Capital with the Ecological Footprint: Applications in Sweden and Subregions', *Ambio* **28**, 604–612.
- Wackernagel, M., Schulz, N. B., Deumling, D., Linares, A. C., Jenkins, M., Kapos, V., Monfreda, C., Loh, J., Myers, N., Norgaard, R., and Randers, J.: 2002, 'Tracking the Ecological Overshoot of the Human Economy', *Proc. Nat. Acad. Sci.* **99**, 9266–9271.
- World Coal Institute: 2000, *Coal: Power for Progress*, World Coal Institute, London.

(Received 26 August 2002; in revised form 25 March 2003)