How Can We Outlive Our Way of Life?

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Abstract

In this paper I outline the rational, science-based arguments that question current wisdom of *replacing* fossil plant fuels (coal, oil and natural gas) with fresh plant agrofuels. This 1:1 replacement is *absolutely* impossible for more than a few years, because of the ways the planet Earth works and maintains life. After these few years, the denuded Earth will be a different planet, hostile to human life. I argue that with the current set of objective constraints a *continuous stable solution* to human life cannot exist in the near-future, unless we *all* rapidly implement much more limited ways of using the Earth's resources, while reducing the global populations of cars, trucks, livestock and, eventually, also humans. To avoid economic and ecological disasters, I recommend to decrease all automotive fuel use in Europe by up to 6 percent per year in 8 years, while switching to the increasingly rechargeable hybrid and all-electric cars, progressively driven by photovoltaic cells. The actual schedule of the rate of decrease should also depend on the exigencies of greenhouse gas abatement. The photovoltaic cell-battery-electric motor system is some 100 times more efficient than major agrofuel systems.

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1 Recommendations

As I show in this paper, the solar power captured by industrial corn, tree, and sugarcane plantations is *minuscule* when compared with our current use of oil (which will last for a limited time only) or the potential provided by photovoltaic solar cells (which will last practically forever). To make things worse, what little solar energy is captured by the plants goes in tandem with a disproportionate environmental damage and negative free energy balance of agrosystems. Therefore, choosing between solar cells and agrofuels, government and industrial funding for renewable energy sources would be spent ∼100 times more wisely on the development of large-throughput, efficient technologies of manufacturing solar cells and batteries.

My recommendations are as follows:

1. As I show here, significantly more efficient individual transportation systems are possible and ought to be implemented. Wherever sensible, individual transportation should be replaced with public transportation systems.

2. The average rate of decline of conventional petroleum production in the world will gradually increase to about 6% per year, and only some of this production will be temporarily replaced by unconventional petroleum sources (tar sands, ultra-heavy oil, oil shale, etc.).

3. Consequently, the overall amount of liquid transportation fuels in the EU ought to decline gradually over the next 8 years from 0 up to 6% per year, and 6% per year thereafter. This scenario would lead to a 50% reduction of liquid transportation fuel consumption in 20 years.

4. The actual schedule of the rate of decrease should also depend on the exigencies of greenhouse gas abatement.

5. To make the scheduled cuts in use of liquid transportation fuels, the EU ought to consider a transition from the current diesel- and gasoline-engine cars to the increasingly rechargeable hybrid cars and, in the longer-term, plug-in hybrids and all-electric cars.

6. Because of the planetary physics of the Earth, agrofuels produced each year will always be inadequate to make up for the decline of liquid transportation fuels from petroleum accumulated over 460 million years or more.

7. Current expansion of agrofuel production *everywhere* is threatening the life-preserving services of the planet Earth and the food resources for the poor majority of the world's population.

8. The EU ought to decide whether industrial agrofuels are bad for the world or not. During the investigation the EU ought to freeze agrofuel use at current levels and stop new agrofuel imports from *all* sources.

9. Photovoltaic cell (PV) and battery R&D and implementation of already existing technologies would have a much greater impact both near- and long-term than agrofuels, and are presently underfunded by two orders of magnitude compared with agrofuels.

10. The EU ought to lead the world in PV cell and battery research.

11. The EU ought *not* subsidize commercial energy sources. Research funding is constructive; subsidizing commercial-scale processes is not. If corn ethanol, cellulosic ethanol, hydrogen buses and other pseudo-green solutions had to be financed by investors instead of taxpayers, they would die a natural death and we could concentrate on approaches like PV that might work.

2 Glossary

To be readable, many of the descriptions below are *not* most rigorous:

Ecosystem: A system that consists of living organisms (plants, bacteria, fungi, animals) and inanimate substrates (soil, minerals, water, atmosphere, etc.), on which these organisms live.

Energy: Energy is the ability of a system to lift a weight in a process that involves no heat exchange (is adiabatic). Total energy is the sum of internal, potential and kinetic energies.

Energy, Free That part of internal energy of a system that can be converted into work. You can think of free energy as the amount of electricity that can be generated from something that changes from an initial to a final state (e.g., by burning a chunk of coal in a stove and doing something with the heat of combustion).

Energy, Primary: Here the heat of combustion (HHV) of a fuel (coal, crude oil, natural gas, biomass, etc.), potential energy of water behind a dam, or the amount of heat from uranium necessary to generate electricity in a nuclear power station.

Exergy: Exergy is equal to the shaft work or electricity necessary to produce very slowly a material in its specified state from materials common in the environment, heat being exchanged with the environment at 1 atmosphere and 15^0 C.

Exergy, Consumption: Cumulative exergy consumption (CExC) is the sum of the exergy of all natural resources used in all the steps of a production process. Cumulative energy consumption (CEnC) is better known, but calculation of CExC is more informative because it accounts for the exergy of non-energetic raw materials (soil, water, air, minerals) extracted from the environment, not just fuels.

Entropy: Entropy is proportional to the part of internal energy that is *transformed* into heat, *not* work, in any process conducted very, very *slowly*. The coefficient of proportionality is 1 over the temperature of the transformation.

Higher Heating Value (HHV): HHV is determined in a sealed insulated vessel by charging it with a stoichiometric mixture of fuel and air (e.g., two moles of hydrogen and air with one mole of oxygen) at 25^0 C. When hydrogen and oxygen are combined, they create hot water vapor. Subsequently, the vessel and its content are cooled down to the original temperature and the HHV of hydrogen is determined by measuring the heat released between identical initial and final temperature of 25^0 C.

Petroleum, conventional: Petroleum, excluding lease gases and condensate, as well as tar sands, oil shales, ultra-deep offshore reservoirs, etc.

System: A region of the world *we pick* and separate from the rest of the world (the *environment*) by an imaginary closed *boundary*. We may not describe a system by what happens inside or outside of it, but only by what *crosses* its boundary. An *open* system allows for matter to cross its boundary, otherwise the system is *closed*.

3 Introduction

The purpose of this paper is to:

1. Show that the current and proposed "cellulosic" ethanol (a "second generation" agrofuel) refineries are inefficient, low energy-density concentrators of solar light.
2. Prove that even if these refineries were marvels of efficiency, they still would be able to make but a dent in our runaway consumption of transportation fuels, because the Earth simply has little or no biomass to spare in the long run.
3. Propose a transportation fuel alternative that does not rely on agrofuels and show why this alternative is at least 100 times more efficient than agrofuel-based systems.

The fundamental energy unit I use in this paper is

$$1 \ \mathsf{exajoule\ (EJ)} \text{ or } 10^{18} \quad \text{joules}$$

A little over four joules heats one teaspoon of water by 1 degree Celsius. One statistical American develops average continuous power of almost exactly 100 W (Patzek, 2007). One exajoule in the digested food feeds amply 300 million people[1] for one year. The actual food available for consumption in the US is ca. 2 $\mathsf{EJ\,yr}^{-1}$, and the entire food system uses $\sim$20 $\mathsf{EJ\,yr}^{-1}$ (Patzek, 2007). Currently, Americans are using about 105 $\mathsf{EJ\,yr}^{-1}$ (340 $\mathsf{GJ\,(yr\text{-}person)}^{-1}$), or 105 times more primary energy than needed as food. The EU countries use 80 $\mathsf{EJ\,yr}^{-1}$ of primary energy or 55% less energy per capita than US.

Current consumption of all transportation fuels in the US is about 33 $\mathsf{EJ\,yr}^{-1}$, see **Figure 1**. A barely visible fraction of this energy comes from corn ethanol. According to current government plans, the amount of ethanol produced in the US will reach 35 billion gallons in 2017, see **Figure 2**, but it is difficult to imagine that a 30 billion gallon per year increase will come from corn ethanol.

Before peaking[2] in 2006, the world production of conventional petroleum grew exponentially at 6.6% per year between 1880 and 1970, see **Figure 3**. The Hubbert curves are symmetrical (Patzek, 2007) and predict world production of conventional petroleum to decline exponentially at a similar rate within a decade from now, or so. This decline can be arrested for a while by heroic measures (infill drilling, horizontal wells, enhanced oil recovery methods, etc.), but the longer it is arrested the more precipitous it will become.

If the current per capita use of petroleum in the US is escalated with the expected growth of US population, the US will have to intercept the *entire* estimated production of conventional petroleum[3] in the world by 2042, see **Figure 4**. In this scenario, the projected *increment* of US petroleum consumption between today and 2042 is equivalent to 270 billion gallons of ethanol.

This brings me to the first major conclusion of this paper:

> With business as usual there is **no** long-term solution to the problem of liquid transportation fuel supply for the US alone, much less for the entire world. For this very reason, the US and the rest of the world soon will be on a head-on collision course.

[1] The US population in 2006.

[2] The short-lived rate peak around 1978 was caused by OPEC limiting its oil production.

[3] I stress again that I am referring to *conventional*, readily-available petroleum. There will be an offsetting production from *unconventional* sources: tar sands, ultra-heavy oil, and natural gas liquefaction, all at very high energy and environmental costs.

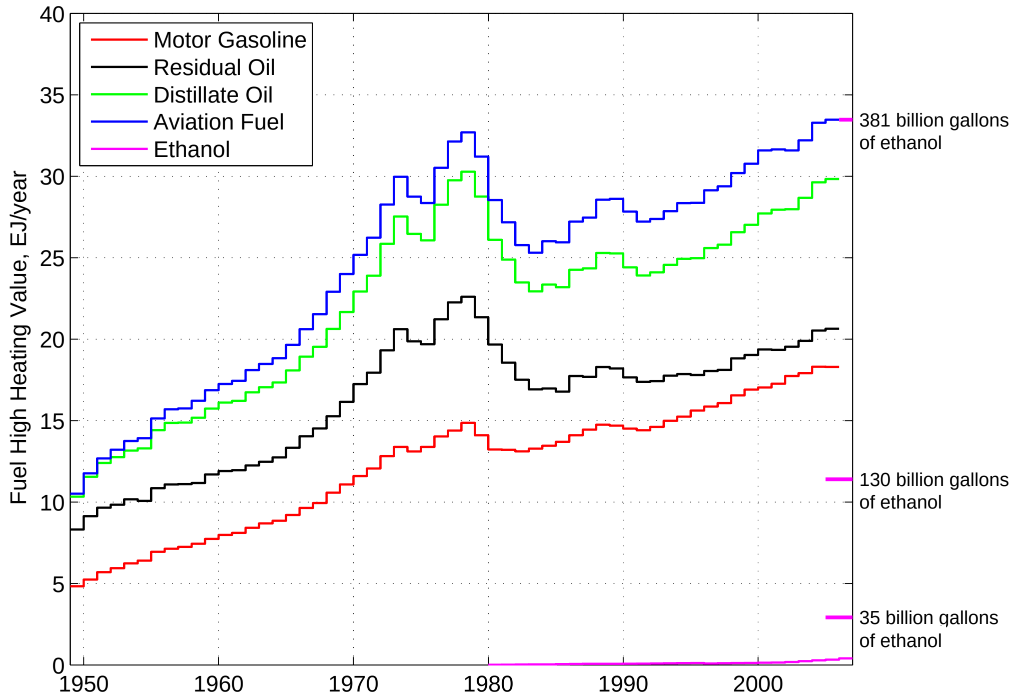

Figure 1: Currently, the US consumes about 33 times more energy in transportation fuels than is necessary to feed its population. This amount of energy is equivalent to 381 billion gallons of ethanol per year. The amount of energy in corn-ethanol is barely visible and it shall always remain so unless we drastically (by a factor of two for starters) lower liquid fuel consumption. Current consumption of ethanol is about 1.2% of the total fuel consumption (without considering energy inputs to the production system). Source: DOE EIA.

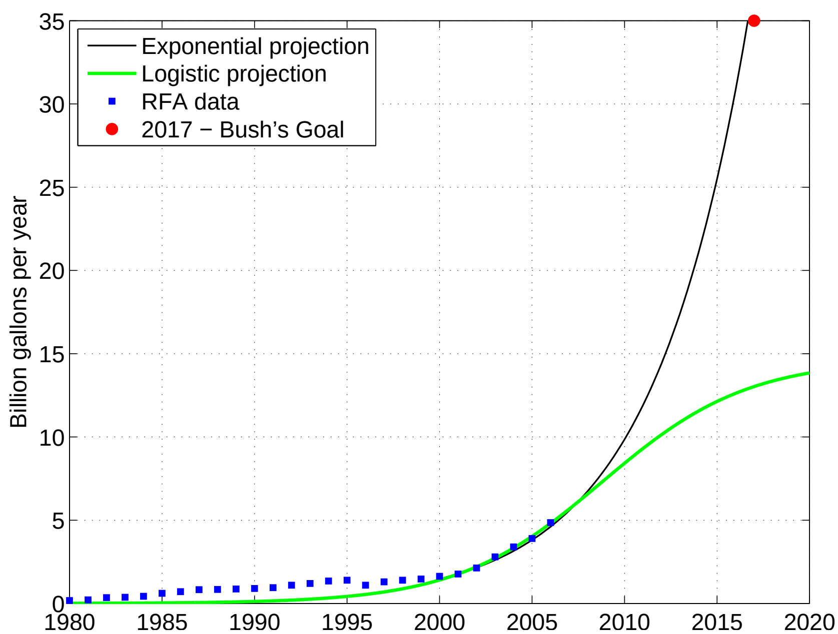

Figure 2: By an exponential extrapolation of ethanol production during the last 7 years at 18.5% per year, one may arrive at 35 billion gallons per year in 2017. The less optimistic logistic fit of the data plateaus at 14 billion gallons per year. Where will the remaining 21 billion gallons of ethanol come from each year? Sources: DOE EIA, Renewable Fuels Association (RFA).

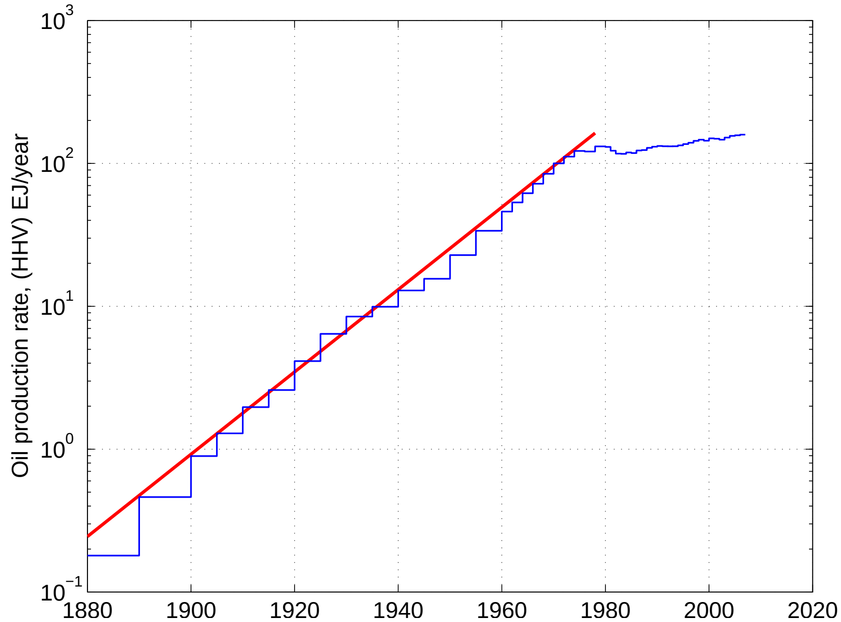

Figure 3: Exponential growth of world crude oil production between 1880 and 1970 proceeded at 6.6% per year. Sources: lib.stat.cmu.edu/DASL/Datafiles/Oilproduction.html, US EIA.

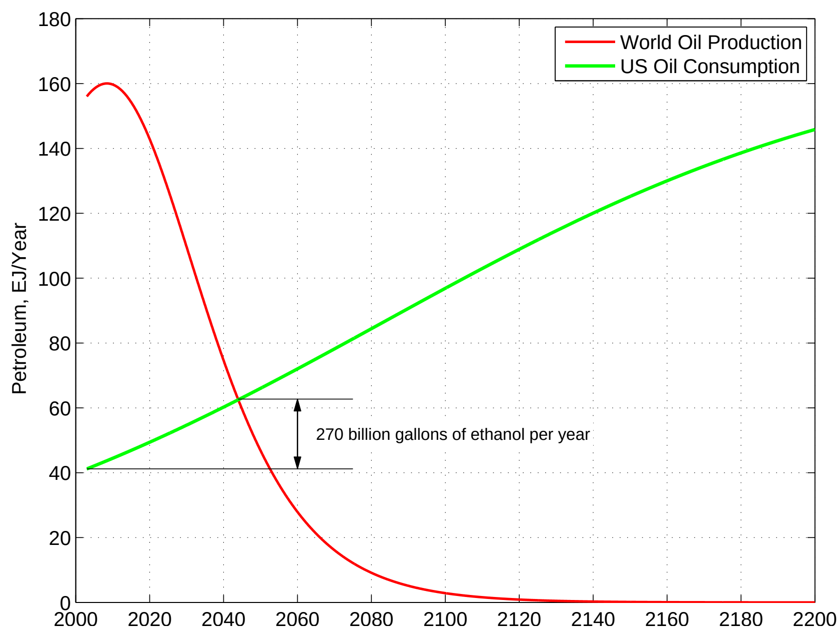

Figure 4: The estimated decline of conventional petroleum production in the world is the red curve. If nothing changes, the current petroleum consumption of petroleum in the US will grow with its estimated population and intercept the global production about 35 years from today. Sources: US EIA, US Census Bureau, (Patzek, 2007).

4 Background

Humans *are* an integral part of a single system made of all life and all parts of the Earth's near-surface shown in **Figure 5**. Thus, as President Vaclav Havel said on July 4, 1994: "Our destiny is not dependent merely on what we do to ourselves but also on what we do for [the Earth] as a whole. If we endanger her, she will dispense with us in the interest of a higher value – life itself." So how to proceed?

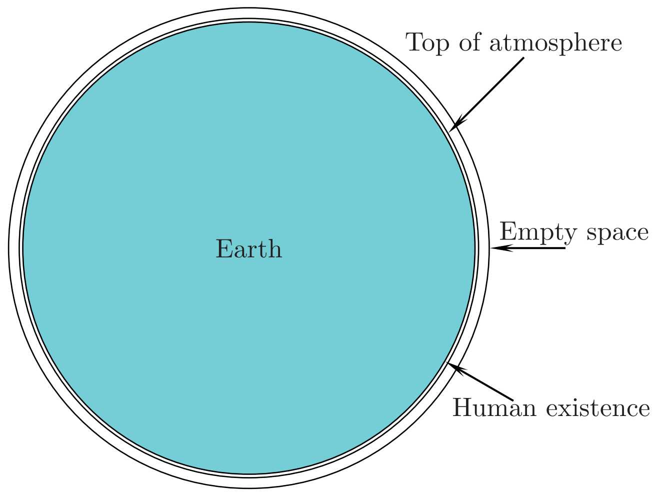

Figure 5: A *system* defined by the mean Earth surface at R_{earth} and the top of the atmosphere at $R_{\text{earth}} + 100$ km, or outer space at $R_{\text{earth}} + 400$ km. Almost all of human existence occurs along the surface of the blue sphere (edge of the blue circle). As drawn here, the line thickness actually exaggerates the *thickness* of the life-giving membrane on which we exist. All radii are drawn to scale.

It appears that humanity's survival is subject to these five constraints:

Constraint 1: An almost exponential rate of growth of human population, see **Figure 6**.

Constraint 2: Too much use of Earth resources; in particular, fossil fuels; and even more specifically, liquid transportation fuels, see **Figure 7**.

Constraint 3: The Earth that is too small to feed in perpetuity 7 billion people and counting, 1 billion cows, and – now – 1 billion cars, see **Figure 8**.

Constraint 4: The ossified political structures in which more is better, and more of the same is also safer.

Constraint 5: A global climate change.

Unfortunately, these five constraints prevent existence of a *stable continuous* solution to human life in the near-future. Alternatively, we may choose from the following two *discontinuous* solutions:

Solution 1: Extinguish ourselves and much of the living Earth, or

Solution 2: Fundamentally and abruptly change, while slowly decreasing our numbers.

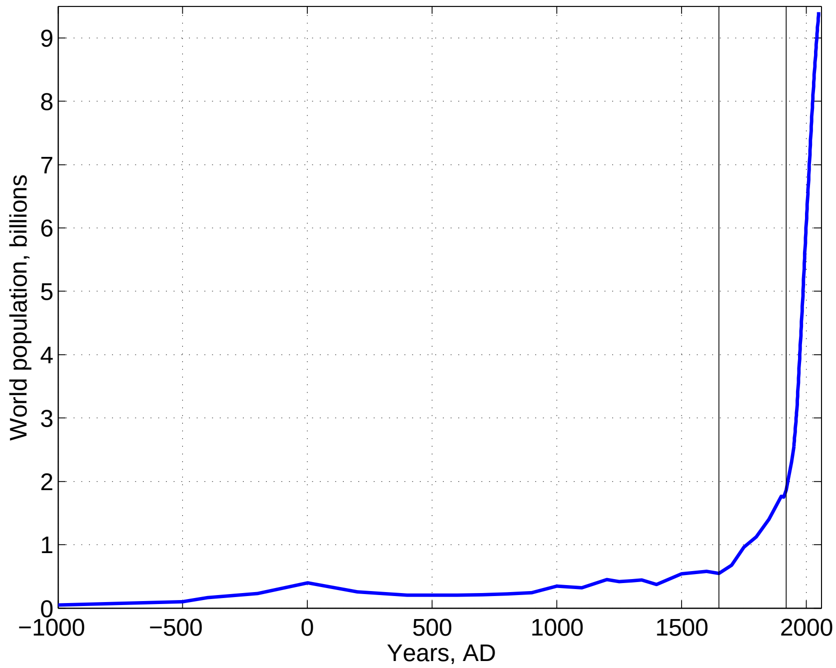

Figure 6: The historical and projected world population. Note the explosive population growth since 1650, the onset of the latest Agricultural Revolution (the left vertical line), and its fastest stage since 1920, the start of large-scale production of ammonia fertilizer by the HABER-BOSCH process (the right vertical line). Imagine yourself standing on the population high in 2050 and looking down. Source: US Census Bureau.

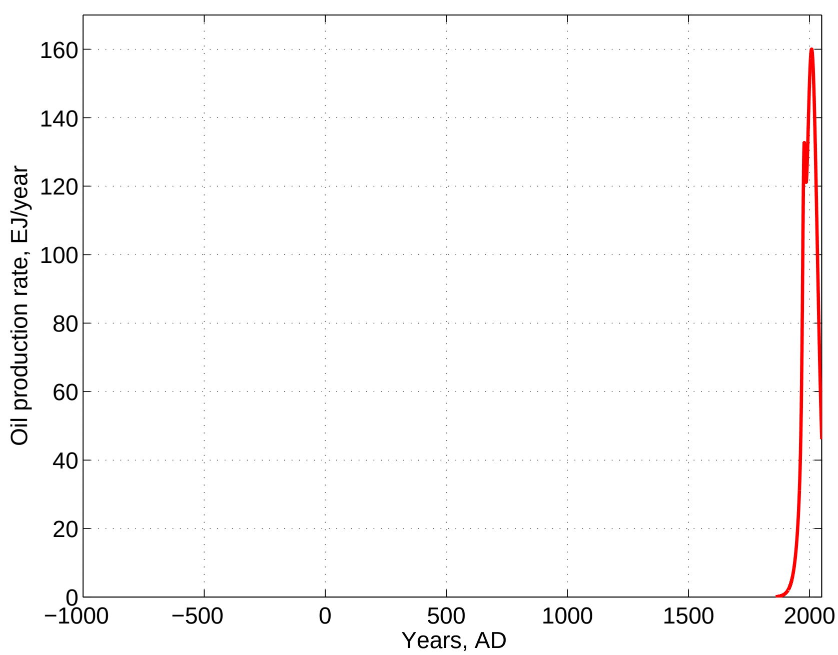

Figure 7: World crude oil production plotted on the same time scale as Figure 6. At today's rate of fossil and nuclear fuel consumption in the US, the global endowment of conventional petroleum would suffice to run the US for 130 years. Of course, by now, one-half of this endowment has been produced, and the US controls little of the remainder.

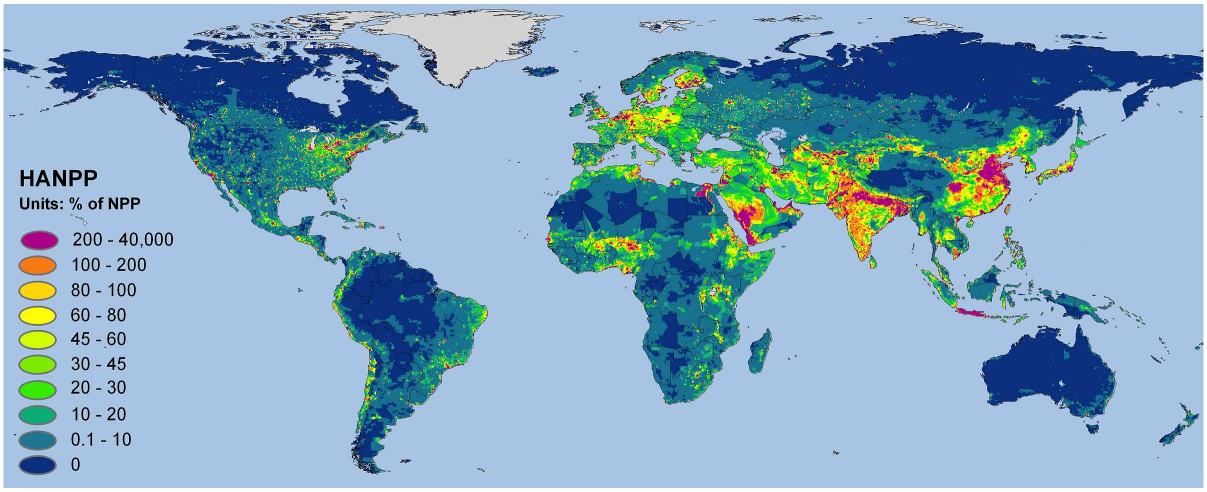

Figure 8: Human-appropriated (HA) Net Primary Production (NPP) of the Earth. Global annual NPP refers to the total amount of plant growth generated each year and quantified as mass of carbon used to build stems, leaves and roots. Note that in the large portions of South and East Asia, Western Europe, Middle East, and eastern US, humans grab up to 1-2 times the net biomass production of local ecosystems. In large cities this ratio increases to 400 times. If this present human commandeering of global NPP is augmented with massive agrofuel production, the Earth ecosystems will collapse. Source: The Visible Earth, NASA images, 06-25-2004, www.nasa.gov/vision/earth/environment/0624_hanpp.html

4.1 Problems with Change

The last time humanity ran mostly on living plant carbon was approximately in 1760. There was 1 billion of us, and we certainly knew how to feed ourselves due to the latest Agricultural Revolution that started in Europe a century earlier (Osborne, 1970). Our food supply problems then had to do with political madness, inaptitude, and greed – just as they do today (Davis, 2002). Today, however, there is almost 7 times more of us, see Figure 6. We can still feed ourselves, but with huge inputs of fossil carbon in addition to fresh plant carbon, minerals, and soil. These inputs also mine fossil water and pollute surface water, aquifers, the oceans, and the atmosphere.

By extrapolating human population growth between 1650 and 1920 to 2007, one estimates 2.2 billion people, who today could live mostly on plant carbon, but use some coal, oil, and natural gas. Therefore, it is reasonable to say that today 4.5 billion people[4] owe their existence to the Haber-Bosch ammonia process and the fossil fuel-driven, fundamentally unstable "green revolution," as well as to vaccines and antibiotics. Agrofuels are a direct outgrowth of the current "green revolution," which may be viewed, see **Appendix B**, as a short-lived but violent disturbance of terrestrial ecosystems on the Earth.

Since most people have cooked or ridden in a vehicle, many feel empowered to talk about *energy* as though they were experts. It turns out, however, that issues of energy supply, use, environmental impacts, and – especially – of *free* energy are too complicated for the *ad lib* homilies we hear every day in the media. Professor Varadaraja Raman, a well-known physicist and humanist, said it best: "A major problem confronting society is the lack of knowledge among the public as to what science is, what constitutes scientific thinking and analysis, and what science's criteria are for determining the correctness of statements about the phenomenological world."

It is a misconception that Constraint 2 can be removed with fresh plant carbon, while

[4] *All* global population increase since 1940.

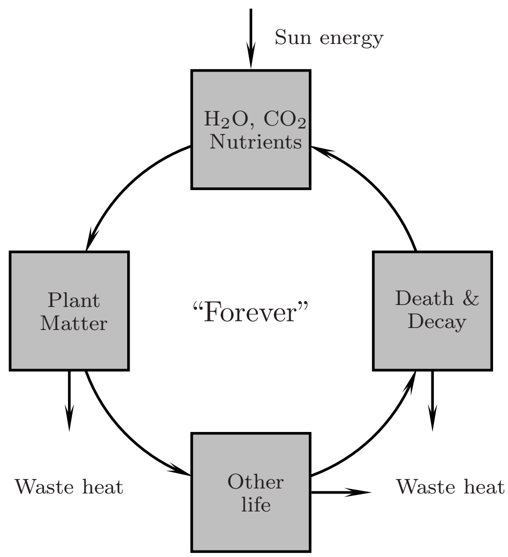

Figure 9: Using sunlight, carbon dioxide, water, and the recycled nutrients, autotrophic plants generate food for heterotrophic fungi, bacteria, and animals. All die in place, and their bodies are decomposed and recycled. Almost *all* mass is conserved, and only low quality heat is exported and radiated back into space. This sustainable *earth household* (ecosystem) may function "forever" compared with the human time scale.

forgetting the scale of Constraint 1 and ignoring Constraint 3. Constraint 4 helps us to maintain that more biomass converted to liquid fuels means more of the same lifestyles, and a stable continuation of the current socioeconomic systems – Constraint 3 be damned.[5] Constraint 5 plays the role of a wild card. Its unknown negative impacts may dwarf everything else I have mentioned in this paper.

This leads me to the second conclusion of this paper, cf. Section 1:

> Business as usual will lead to a complete and practically immediate crash of the technically advanced societies and, perhaps, all humanity. This outcome will not be much different from a collapse of an overgrown colony of bacteria on a petri dish when its sugar food runs out and waste products build up. Today, the human "petri dish" is Earth's surface in Figure 5, and "food" is the living matter and water we consume and the ancient plant products and minerals (oil, natural gas, coal, etc.) we mine and burn.

The Earth operates in *endless* cycles as in **Figure 9**, and modern humans race along *short* line segments, as in **Figures 10** and **7**. At each turn of her cycles, the Earth renews herself, but humans are about to wake up inside a huge toxic waste dump with nowhere to go.

4.2 But Plant Biology is Different!

Recently I heard an agrofuel "expert" exclaiming: "...Biotechnology is not subject to the same laws of chemistry and physics as other technologies. In biology anything is possible, and the sky is the limit!" This statement contradicts the Second Law of thermodynamics and is false.

[5]In his review, Dr. Silin has pointed out to me a beautiful paper by von Engelhardt, Hubbert, and others (1975). This paper contains several ideas similar or identical to the ideas expressed here. The following statement is particularly salient: "This [*collective human experience of exponential growth*] has fostered the popular notion that growth is synonymous with progress and that further improvements in the quality of human life will be contingent upon steady or increasing rate of growth, even though growth at an increasing rate cannot be sustained indefinitely within the physical limits of a finite earth."

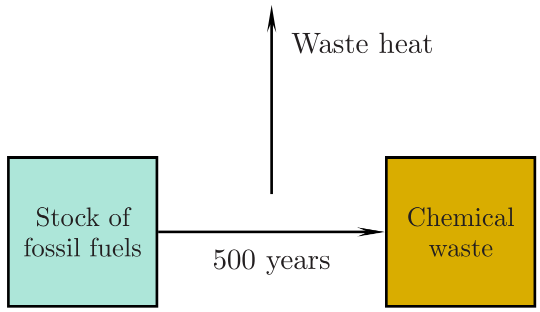

Figure 10: A linear process of converting a stock of fossil fuels into waste matter and heat cannot be sustainable. The waste heat is exported to the universe, but the chemical waste accumulates. To replenish some of the fossil fuel stock, it will take another 50 to 400 million years of photosynthesis, burial, and entrapment.

The rate of entropy production in any natural (irreversible) process, such as photosynthesis or plant growth, is a measure of the dissipation (energy wasted to heat generation) in that process. As observed by Ross and Vlad in their brilliant paper (2005), there exists an old "principle" in the literature (Prigogine, 1945) that says: If a steady state is close enough to equilibrium, the rate of entropy production has an extremum at that state. This "principle" is mathematically correct if and only if thermodynamic fluxes (of mass, heat, etc.) and forces (concentration gradient, temperature gradient, etc.) are proportional and the coefficients of proportionality form a symmetric matrix (De Groot and Mazur, 1962). Later on, Glansdorff and Prigogine (1971) restated the "principle" with the thought that close to equilibrium the proportionality between fluxes and forces becomes nearly true: "It is easy to show that if the steady states occur sufficiently close to equilibrium states they may be characterized by an extremum principle according to which the entropy production has its minimum value at the steady-state compatible with the prescribed conditions (constraints) to be specified in each case."

Unfortunately this incorrect restatement has been repeated many times, especially in connection with biochemical and biological applications, where there is a tendency to present the principle of minimum entropy production in even vaguer terms, as a fundamental law of nature, which is supposed to be valid for any evolution equations. For example, (Voet and Voet, 2004) in a widely used text, state that "Ilya Prigogine, a pioneer in the development of irreversible thermodynamics, has shown that a steady state produces the maximum amount of useful work for a given energy expenditure under the prevailing conditions. The steady state of an open system is therefore its state of maximum thermodynamic efficiency." This statement is not true in general.

Ross and Vlad (2005) have proven by counterexamples that real systems in arbitrary non-equilibrium states, for example photosynthesizing higher plants or algae, or bacteria, produce more entropy than calculated from the "principles" above. Also, based on Ross and Vlad's results, one can show that the losses associated with irreversible heat transfer in a plant due to an increase of the heat flux from photosynthesis are proportional to the square of this flux. In other words, if the heat-generating photosynthetic activities increase by a factor of two, the corresponding energy losses *must* increase by a factor of four. This observation leads to the third conclusion of this paper:

Because of the thermodynamics of irreversible processes, the promises to increase the rate of plant photosynthesis significantly are *empty*. A higher photosynthetic rate would result in the disproportionately higher water transpiration fluxes to cool the plants, larger root systems, higher respiration rates, and higher overall water requirements of these plants. It is not a coincidence that – given all contradictory environmental factors – over the last 3.5 billion years Mother Nature has fine-tuned plant photosynthesis to its current efficiency. Water, not solar energy conversion, is the real limiting factor of plant efficiency.

5 Plan of Attack

As you are beginning to suspect, it is not sufficient to limit oneself just to discussing liquid transportation fuels and their future biological sources. These transportation fuels intrude upon every other aspect of life on the Earth: Availability of clean water to drink and clean air to breathe, healthy soil and healthy food supply, destruction of biodiversity and essential planetary services in the tropics, acceleration of global climate change, and so on.

As with many important policy-making decision processes, I start from the end, here the cellulosic ethanol refineries. This is where most public money, attention, and hope are. I show that these refineries are inefficient compared with the existing petroleum- and corn-based refineries, and are difficult to scale up.

Then I return to the beginning and show that even *if* the cellulosic biomass refineries were marvels of efficiency, they still could *not* maintain our current lifestyles by a long stretch, simply because the Earth will not give us the extra biomass needed to keep on existing as we do. For a while we might continue to *rob* this biomass from the poor tropics, but the results are already disastrous for all humanity, see **Figure 11**.

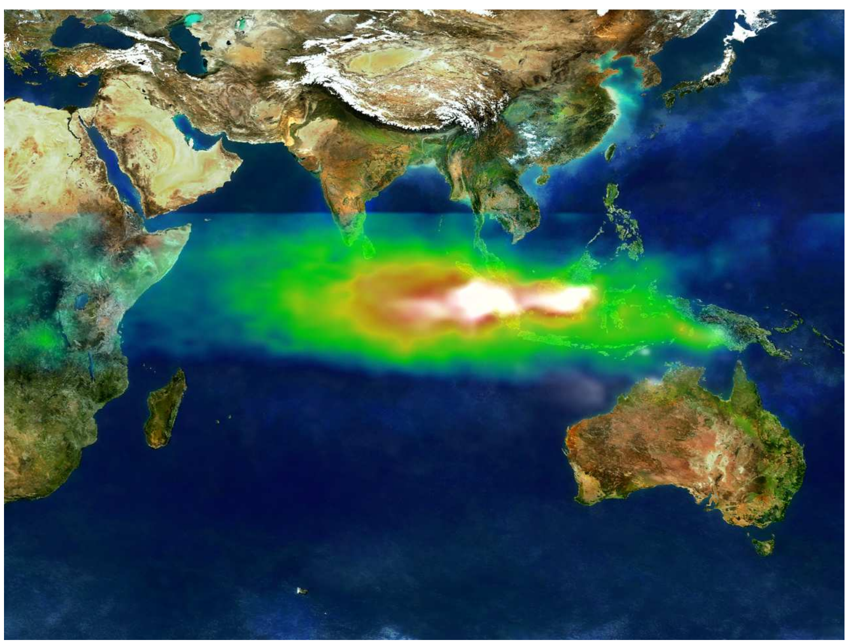

Figure 11: In the fall of 1997, an orgy of 176 fires in Indonesia burned 12 million ha of virgin forest and generated as much greenhouse gases as the US in *one year*. 133 of these illegal fires were started by oil palm plantation/logging companies to steal old-growth trees and burn the rest for new plantations. The smoke and ozone plume had global extent. Sources: NASA's Earth Probe Total Ozone Mapping, Spectrometer (TOMS), October 22, 1997; (Schimel and Baker, 2002; Page et al., 2002; Patzek and Patzek, 2007).

Once I have demonstrated the utter impossibility of replacing liquid transportation fuels with agrofuels and conveyed the damage to the planet their production is causing now, I propose a positive solution that involves photovoltaics and batteries.

6 Efficiency of Cellulosic Ethanol Refineries

I start from a "reverse-engineering" calculation of energy efficiency of cellulosic ethanol production in an *existing* Iogen pilot plant, Ottawa, Canada. I then discuss the inflated energy efficiency claims of five out-of-six recipients of $385 millions of DOE grants to develop cellulosic ethanol refineries.

6.1 Iogen Ottawa Facility

Wheat, oat, and barley straw are first pretreated with sulfuric acid and steam. Iogen's patented enzyme then breaks the cellulose and hemicelluloses down into six- and five-carbon sugars, which are later fermented and distilled into ethanol. Normal yeast does not ferment the 5-carbon sugars, so genetically modified, delicate and patented yeast strains are used. Iogen's plant has capacity of 1 million gallons of ethanol per year. The only *published* ethanol production is shown in **Figure 12**.

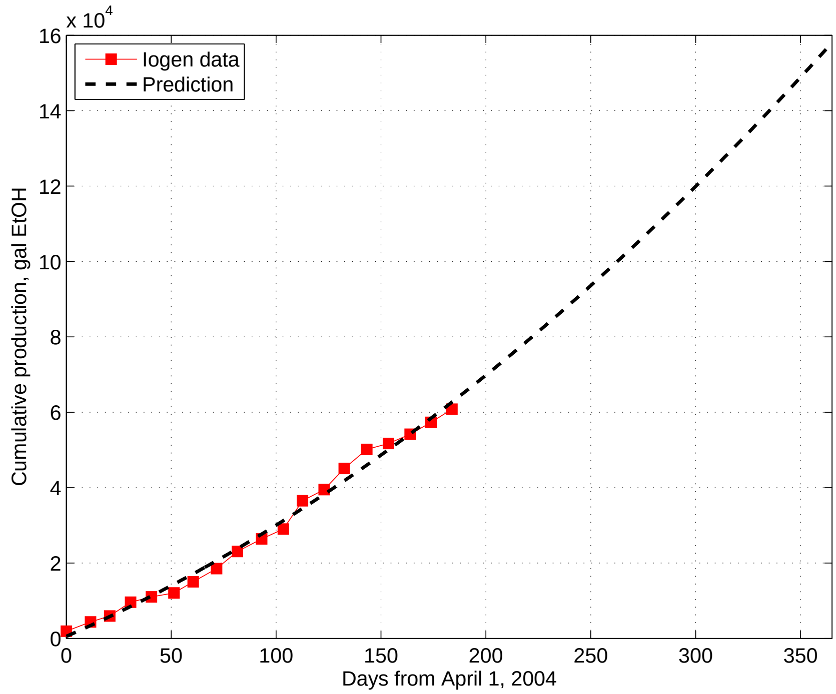

Figure 12: Ethanol production in Iogen's Ottawa plant. Extrapolation to one year yields 158 000 gallons. Note that the data points are evenly spaced as they should be for regularly scheduled batches. Source: Jeff Passmore, Executive Vice President, Iogen Corporation, *Cellulose ethanol is ready to go*, Presentation to Governor's Ethanol Coalition & US EPA Environmental Meeting "Ethanol and the Environment," Feb. 10, 2006.

From Figure 12 and a presentation[6] by Maurice Hladik, Director of Marketing, Iogen Corp., the following can be deduced:

- 158 000 gallons/year of anhydrous ethanol (EtOH), or 10 bbl EtOH/day = 6.7 bbl of

[6] *Cellulose Ethanol is ready to go*, Renewable Fuels Summit, June 12, 2006.

equivalent gasoline/day were actually produced. In press interviews, Iogen claims to be producing 790 000 gallons of ethanol[7] per year.

- There exists $2 \times 52000 = 104000$ gallons of fermentation tank volume.
- The actual ethanol production and tank volume give the ratio of 1.5 gallons of ethanol per gallon of fermenter and per year.
- I assume 7-day batches + 2-day cleanups.
- Thus, there is ca. 4% of alcohol in a batch of industrial wheat-straw beer, in contrast to 12 to 16% of ethanol in corn-ethanol refinery beers.

Since wheat is the largest grain crop in Canada, I use its straw as a reference (the other two straws are similar). On a dry mass basis (dmb), wheat straw has 33% of cellulose, 23% of hemicelluloses, and 17% total lignin.[8] Other sources report 38%, 29%, and 15% dmb, respectively, see (Lee et al., 2007) for a data compilation. These differences are not surprising, given experimental uncertainties and variable biomass composition. To calculate ethanol yield, I use the more optimistic, second set of data. The respective conversion efficiencies, assumed after Badger (2002), are listed in **Table 1**.

Table 1: Yields of ethanol from cellulose and hemicellulose. Source: Badger (2002)

Step	Cellulose	Hemicellulose
Dry straw	1 kg	1 kg
Mass fraction	×0.38	×0.29
Enzymatic conversion efficiency	×0.76	×0.90
Ethanol stoichiometric yield	×0.51	×0.51
Fermentation efficiency	×0.75	×0.50
EtOH Yield, kg	0.111	0.067

The calculated ethanol yield, 0.18 $\mathsf{kg\ EtOH\ (kg\ straw\ dmb)^{-1}}$, is somewhat less than a recently reported maximum ethanol yield of 0.24 kg/kg (Saha et al., 2005) achieved in 500 mL vessels, starting from 48.6% of cellulose. Simultaneous saccharification and fermentation yielded 0.17 kg/kg, see Table 5 in Saha et al. (2005).

Because enzymatic decomposition of cellulose and hemicelluloses is inefficient, the resulting dilute beer requires 2.4 times more energy to distill than the average 15 MJ L^{-1} in an average ethanol refinery (Patzek, 2004; Patzek, 2006a), see **Figure 13**.

One may argue that Iogen's Ottawa facility is for demonstration purposes only and that the saccharification and fermentation batches were not regularly scheduled. In this case, an alternative calculation yields the same result: At about 0.2 to 0.25 kg of straw/L, the mash is barely pumpable. With Badger's yield of 0.18 kg/kg of EtOH, the highest ethanol yield is 3.5 to 4.4 % of ethanol in water.

The higher heating value (HHV) of ethanol is 29.6 $\mathsf{MJ\ kg^{-1}}$ (Patzek, 2004). The HHV of wheat straw is 18.1 $\mathsf{MJ\ kg^{-1}}$ (Schmidt et al., 1993) and that of lignin 21.2 $\mathsf{MJ\ kg^{-1}}$ (Domalski et al., 1987).

With these inputs, the first-law (energy) efficiency of Iogen's facility is

$$\eta = \frac{0.18 \times 29.6}{1 \times 18.1 + 0.18 \times 2.4 \times 15/0.787 - 0.15 \times 21.2} \approx 20\% \tag{1}$$

[7] *It's Happening in Ottawa – Grains become fuel at the world's first cellulosic ethanol demo plant*, Grist, Sharon Boddy, 12 Dec., 2006. It is possible that the notoriously innumerate journalists confused liters with gallons: 790 000 liters is 200 000 gallons, much closer to the published data from Iogen.

[8] Biomass feedstock composition and property database. Department of Energy, Biomass Program, www.eere.energy.gov/biomass/progs/search1.cgi, accessed July 25, 2007.

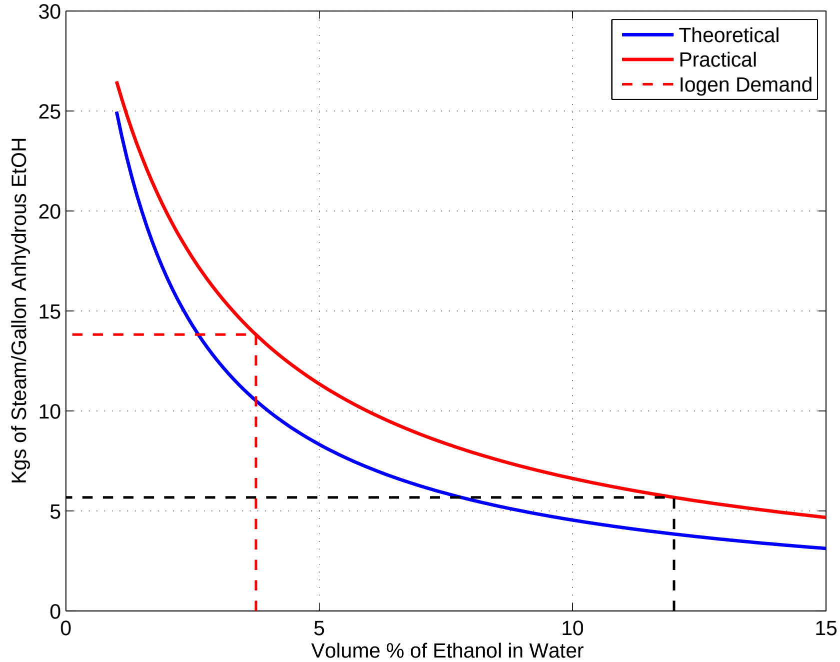

Figure 13: Steam requirement in ethanol beer distillation. The 3.7% beer requires 2.4 times more steam than a 12% beer. Source (Jacques et al., 2003).

where the density of ethanol is 0.787 $\mathsf{kg\ L^{-1}}$ and the entire HHV of lignin was used to offset distillation fuel (another optimistic assumption for the wet separated lignin). This calculation disregards the energy costs of high-pressure steam treatments of the straw at 120 or 140 ^{0}C, and the separated solids at 190 ^{0}C, sulfuric acid and sodium hydroxide production, etc. Also, the complex enzyme production processes must use plenty of energy.

This analysis leads to the fourth conclusion:

> The Iogen plant in Ottawa, Canada, has operated well below name plate capacity for three years. Iogen should retain their trade secrets, but in exchange for the significant subsidies from the US and Canadian taxpayers they should tell us what the annual production of alcohols *was*, how much straw was used, and what the fossil fuel and electricity inputs were. The ethanol yield coefficient in kg of ethanol per kg straw dmb is key to public assessments of the new technology. Similar remarks pertain to the Novozymes projects heavily subsidized by the Danes. Until an existing pilot plant provides real, independently verified data on yield coefficients, mash ethanol concentrations, etc., all proposed cellulosic ethanol refinery designs are *speculation*.

6.2 Proposed Cellulosic Ethanol Refineries

Now I present at *face value* the stated energy efficiencies[9] of the six proposed[10] cellulosic ethanol plants awarded 385 million USD by the US Department of Energy.

Figure 14 ranks the rather imaginary claims of 5 out of 6 award recipients. For calibration, after 87 years of development and optimization, the actual energy efficiency of Sasol's Fischer-Tropsch coal-to-liquid fuels plants is about 42% (Steynberg and Nel, 2004). The average

[9]The HHV of ethanol out divided by the HHV of biomass in. No fossil fuels inputs into the plants and the raw materials they use are accounted for.

[10]Environmental and Energy Study Institute, 122 C STREET, N.W., SUITE 630 WASHINGTON, D.C., 20001, www.eesi.org/publications/Press%20Releases/2007/2-28-07_doe_biorefinery_awards.pdf

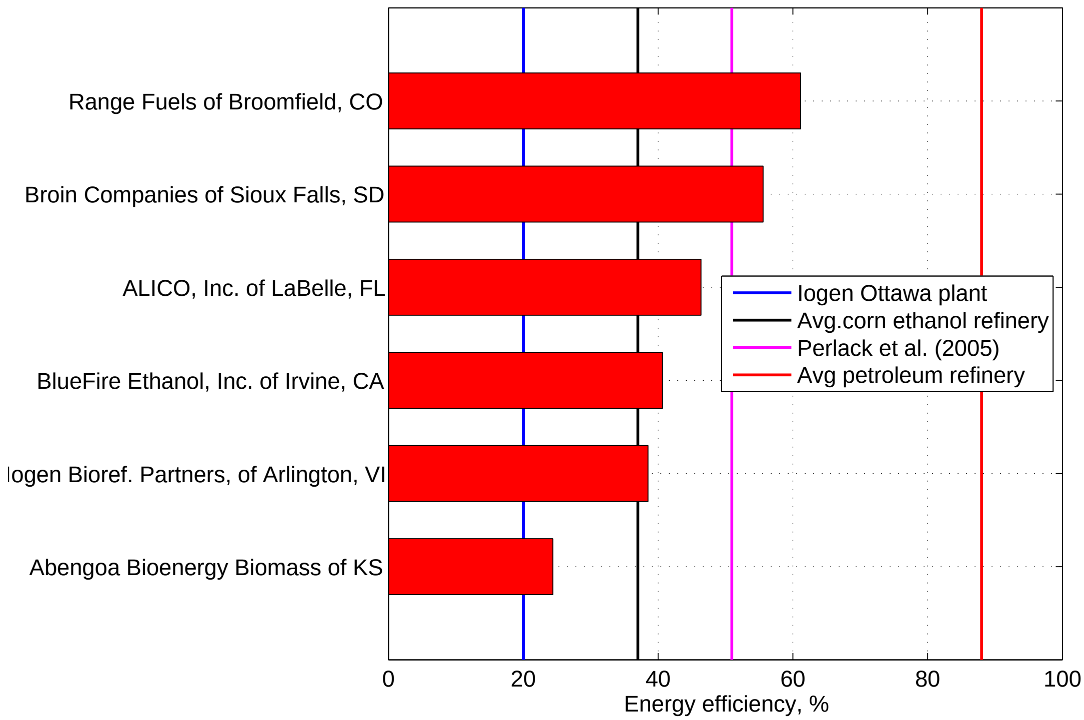

Figure 14: Stated energy efficiencies of the six future cellulosic ethanol refineries awarded $385 millions in DOE grants. The calculated energy efficiency (left line) of an existing cellulosic ethanol refinery in Ottawa serves to calibrate the rather inflated efficiency claims of 5/6 grant recipients. Energy efficiencies of an average ethanol refinery and petroleum refinery (Patzek, 2006a) are also shown (second and last line from the left).

energy efficiency of the highly optimized corn ethanol refineries is 37% (not counting grain coproducts as fuels). An average petroleum refinery is about 88% energy-efficient.[11] For details, see (Patzek, 2006b; Patzek, 2006c; Patzek, 2006a). The DOE/USDA report by Perlack et al. (2005) has led to the claims by an influential venture capitalist, Mr. Vinod Khosla (2006), of being able to produce 130 billion gallons of ethanol from 1.4 billion tons of biomass (dmb), apparently at a 52% thermodynamic efficiency.

To see how very different the new fossil-energy-free world will be, let's compare power from Iogen's plant with that from an oil well in the US. Ever more *power* is what we must have to continue our current way of life (cf. Footnote 5). Iogen's plant delivers the power of 7 barrels of oil per day (68 kW). Average power of petroleum wells in the largely oil-depleted US was 10 bbl $(\text{well-day})^{-1}$ in 2006[12] (98 kW). Therefore, an average US petroleum well delivers more power than a city-block size Iogen facility in Ottawa and its area of straw collection, probably 50 km in radius, which at this time is saturated with fossil fuels outright and their products (ammonia fertilizers, field chemicals, roads, etc.). The petroleum well also uses little input power; unfortunately, soon petroleum will not be a transportation option. Such is the difference between solar energy stocks (depletable fossil fuels) and flows (daily photosynthesis).

One can calculate that an average agricultural worker in the US uses 800 kW of fossil energy inputs and outputs 3000 kW. An average oil & gas worker in California uses 2800 kW of fossil energy inputs and outputs 14,500 kW. Due to fossil energy and machines these two workers are supermen, each capable of doing the work of 8000 and 28000 ordinary humans, respectively. These two fellows are about to become human again, and we need to get used to this idea.

[11] As pointed out by Drs. John Benemann and John Newman, this comparison may be unfair. No liquid fuel technology will ever match petroleum refining, but petroleum-derived fuels will not last for very long.

[12] See www.eia.doe.gov/emeu/aer/txt/ptb0502.html, accessed July 25, 2007.

Now, you may want to go back to **Section 4.1** and reread it.

7 Where Will the Agrofuel Biomass Come From?

Collectively, the EU and the US have spent billions of dollars to be able to construct the inefficient behemoth factories, which in the distant future might ingest megatonnes or gigatonnes of apparently free biomass "trash" and spit out priceless liquid transportation fuels. It is therefore prudent to ask the following question: Where, how much, and for how long will the Earth produce the extra biomass to quench our unending thirst to drive 1 billion cars and trucks?

The answer to this question is immediate and unequivocal: Nowhere, close to nothing, and for a very short time indeed. On the average, our planet has **zero** excess biomass at her disposal.

7.1 Useful Terminology

Several different ecosystem[13] productivities, i.e., measures of biomass accumulation per unit area and unit time have been used in the ecological literature, e.g., (Reichle et al., 1975; Randerson et al., 2001) and many others. Usually this biomass is expressed as grams of carbon (C) per square meter and per year, or as grams of water-free biomass (dmb) per square meter and year.[14] The conversion factor between these two estimates is the carbon mass fraction in the fundamental building blocks of biomass, CH_xO_y, where x and y are real numbers, e.g., 1.6 and 0.6, that express the overall mass ratios of hydrogen and oxygen to carbon. The following definitions are common in ecology:

1. *Gross* Primary Productivity, GPP = mass of CO_2 fixed by plants as glucose.

2. Ecosystem respiration, R_e = mass of CO_2 released by metabolic activity of autotrophs, R_a, and heterotrophs (consumers and decomposers), R_h:

$$R_e = R_a + R_h \tag{2}$$

   where decomposers are defined as worms, bacteria, fungi, etc. Plants respire about 1/2 of the carbon available from photosynthesis after photorespiration, with the remainder available for growth, propagation, and litter production, see (Ryan, 1991). Heterotrophs respire most, 82 to 95%, of the biomass left after plant respiration (Randerson et al., 2001).

3. *Net* Primary Productivity, $\mathsf{NPP} = \mathsf{GPP} - R_a$.

4. Net *Ecosystem* Productivity

$$\mathsf{NEP} = \mathsf{GPP} \text{ - } R_e \text{ - Non-}R \text{ sinks and flows} \tag{3}$$

   The older NEP definitions would usually neglect the non respiratory losses, e.g., (Reichle et al., 1975). All ecological definitions of NEP I have seen, lump incorrectly mass flows and mass sources and sinks, calling them "fluxes," see, e.g., (Randerson et al., 2001; Lugo and Brown, 1986). For more details, see **Appendix B**.

The typical net primary productivities of different ecosystems are listed in **Appendix C**.

[13] An ecosystem is defined in more detail in **Appendix A**.

[14] Or as kilograms (dmb) of biomass per hectare and per year.

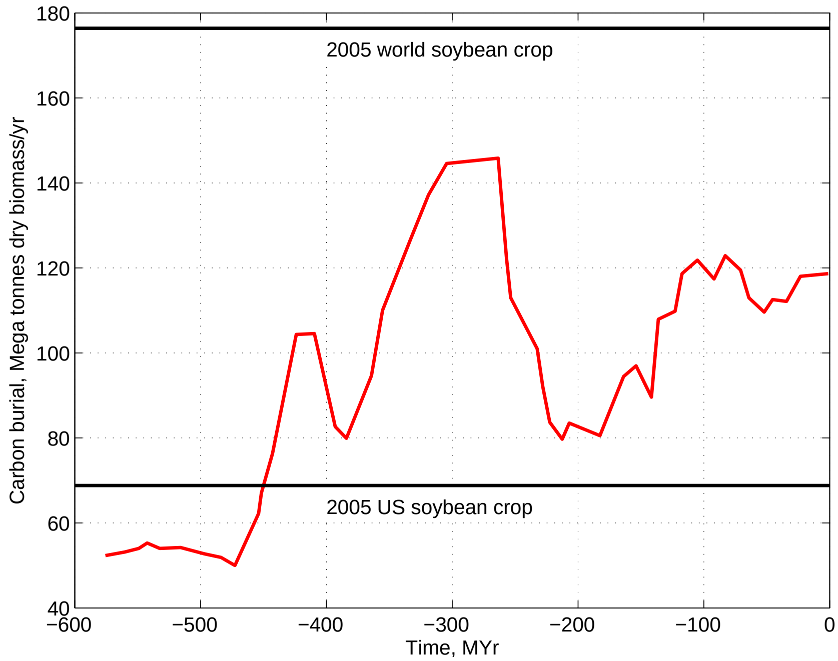

Figure 15: Plot of global organic carbon burial during the Phanerozoic eon. Carbon burial rate modified from BERNER (2001; 2003). The units of carbon burial have been changed from 10^{18} mol C Myr^{-1} to Mt biomass yr^{-1}. The very high carbon burial values centered around 300 Myr ago are due predominantly to terrestrial carbon burial and coal formation. Most plants have been buried in swamps, shallow lakes, estuaries, and shallow coastal waters. Note that historically the average rate of carbon burial on the Earth has been *tiny*, half-way between the US- and world crops of soybeans in 2005. This burial rate amounts to $120 \times 10^6/110 \times 10^9 \times 100\% = 0.1\%$ of global NPP of biomass.

7.2 Plant Biomass Production

The reason for the Earth recycling all of her material parts can be explained by looking again at Figure 5. The Earth is powered by the sun's radiation that crosses the outer boundary of her atmosphere and reaches her surface. The Earth can export into outer space long-wave infrared radiation.[15] But, because of her size, the Earth holds on to all mass of all chemical elements, except perhaps for hydrogen. By maintaining an oxygen-rich atmosphere, *life* has managed to prevent the airborne hydrogen from escaping Earth's gravity by reacting it back to water (and destroying ozone).

> If all mass must stay on the Earth, all her households must recycle everything; otherwise internal chemical waste would build up and gradually kill them. Mother Nature does not usually do toxic waste landfills and spills.

In a mature ecosystem, one species' waste must be another species' food and no *net* waste is ever created, see Figure 9. The little imperfections in the Earth's *surface* recycling programs have resulted in the burial of a remarkably *tiny* fraction of plant carbon in swamps, lakes, and shallow coastal waters[16], see **Figure 15**. Very rarely the violent anoxic events would kill most of life in the oceanic waters and cause faster carbon burial. Over the last 460,000,000 years (and

[15] Therefore, the Earth is an *open* system with respect to electromagnetic radiation. Life could emerge on her and be sustained for 3.5 eons because of this openness.

[16] Much of this burial has been eliminated by humans. We have paved over most of the swamps and destroyed much of the coastal mangrove forests, the highest-rate local sources of terrestrial biomass transfer into seawater.

going back all the way to 2,500,000,000 years ago), the Earth has gathered and transformed *some* of the buried ancient plant mass into the fossil fuels we love and loath so much.

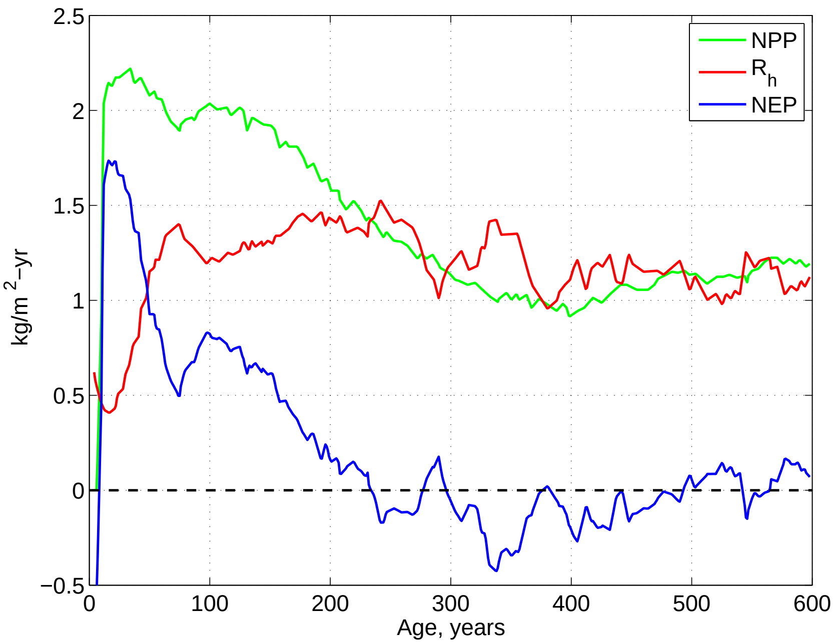

Figure 16: Forest ecosystem biomass fluxes simulated for a typical stand in the H. J. ANDREWS Experimental Forest. The Net Primary Productivity (NPP), the heterotrophic respiration (R_h), and the Net Ecosystem Productivity (NEP) are all strongly dependent on stand age. This particular stand builds more plant mass than heterotrophs consume for 200 years. After that, for any particular year, an old-growth stand is in equilibrium and its average net ecosystem productivity is zero. Adapted from Songa & Woodcock (2003).

The proper mass balance of carbon fluxes in terrestrial ecosystems, see **Appendix B**, confirms the compelling thermodynamic argument that sustainability of any ecosystem requires *all* mass to be conserved on the average. The larger the spatial scale of an ecosystem and the longer the time-averaging scale are, the stricter adherence to this rule must be. Such are the laws of nature.

Physics, chemistry and biology say clearly that there can be *no* sustained net mass *output* from any ecosystem for more than a few years. A young forest in a temperate climate grows fast in a clear-cut area, see **Figure 16**, and transfers nutrients from soil to the young trees. The young trees grow very fast (there is a positive NPP), but the amount of mass accumulated in the forest is small. When a tree burns or dies some or most of its nutrients go back to the soil. When this tree is logged and hauled away, almost no nutrients are returned. After logging young trees a couple of times the forest soil becomes depleted, while the populations of insects and pathogens are well-established, and the forest productivity rapidly declines (Patzek and Pimentel, 2006). When the forest is allowed to grow long enough, its net ecosystem productivity becomes **zero** on the average.

Therefore, in order to export biomass (mostly water, but also carbon, oxygen, hydrogen and a plethora of nutrients) an ecosystem must import equivalent quantities of the chemical elements it lost, or decline irreversibly. Carbon comes from the atmospheric CO_2 and water flows in as rain, rivers and irrigation from mined aquifers and lakes. The other nutrients, however, must be rapidly *produced* from ancient plant matter transformed into methane, coal, petroleum, phosphates[17], etc., as well as from earth minerals (muriate of potash, dolomites,

[17]Over millions of years, the annual cycles of life and death in ocean upwelling zones have propelled sedimentation of organic matter. Critters expire or are eaten, and their shredded carcasses accumulate in sediments as fecal

etc.), – all *irreversibly* mined by humans. Therefore, to the extent that humans are no longer integrated with the ecosystems in which they live, they are doomed to extinction by exhausting all planetary stocks of minerals, soil and clean water. The question is not *if*, but *how fast*?

It seems that with the exponentially accelerating *mining* of global ecosystems for biomass, the time scale of our extinction is shrinking with each crop harvest. Compare this statement with the feverish proclamations of sustainable biomass and agrofuel production that flood us from the confused media outlets, peer-reviewed journals, and politicians.

7.3 Is There Any Other Proof of NEP = 0?

I just gave you an abstract proof of no trash production in Earth's Kingdom, except for its dirty human slums.

Are there any other, more direct proofs, perhaps based on measurements? It turns out that there are two approaches that complement each other and lead to the same conclusions. The first approach is based on a top-down view of the Earth from a satellite and a mapping of the reflected infrared spectra into biomass growth. I will summarize this proof here. The second approach involves a direct counting of all crops, grass, and trees, and translating the weighed or otherwise measured biomass into net primary productivity of ecosystems. Both approaches yield very similar results.

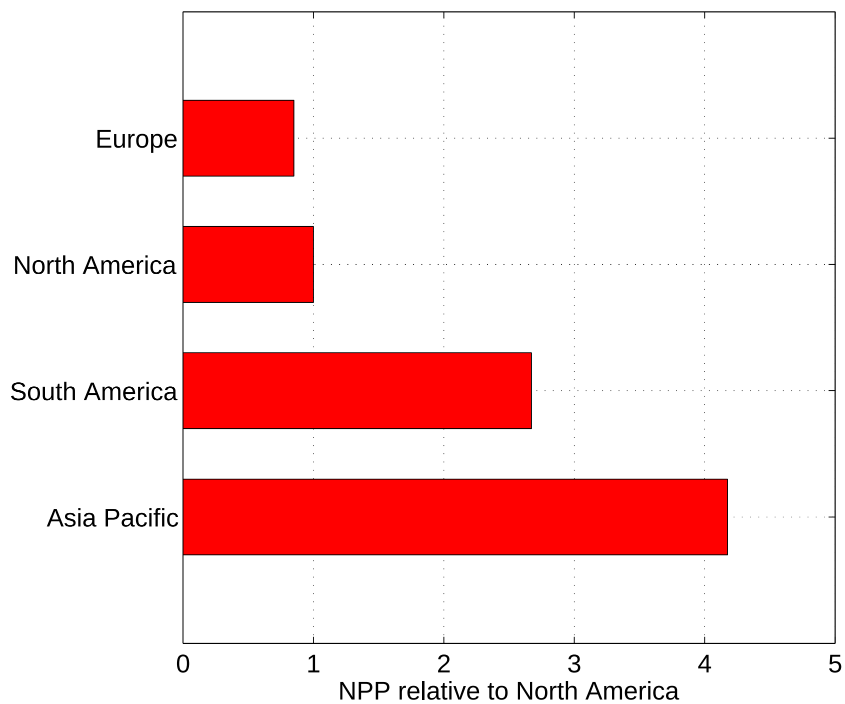

Figure 17: NPP's of Asia-Pacific, South America, and Europe – relative to North America. Source: MOD17A2/A3 model.

pellets and as gelatinous flocs termed marine snow. Decay of some of this deposited organic matter consumes virtually all of the dissolved oxygen near the seafloor, a natural process that permits formation of finely-layered, organic-rich muds. These muds are a biogeochemical "strange brew," where calcium – derived directly from seawater or from the shells of calcareous plankton – and phosphorus – generally derived from bacterial decay of organic matter and dissolution of fish bones and scales – combine *over geological time* to form pencil-thin laminae and discrete sand to pebble-sized grains of phosphate minerals. Source: GRIMM (1998).

7.4 Satellite Sensor-based Estimates

Global ecosystem productivity can be estimated by combining remote sensing with a carbon cycle analysis. The US National Aeronautics and Space Administration (NASA) Earth Observing System (EOS) currently "produces a regular global estimate of gross primary productivity (GPP) and annual net primary productivity (NPP) of the entire terrestrial earth surface at 1-km spatial resolution, 150 million cells, each having GPP and NPP computed individually" (Running et al., 2000). The MOD17A2/A3 User's Guide (Heinsch and et al., 2003) provides a description of the Gross and Net Primary Productivity estimation algorithms (MOD17A2/A3) designed for the MODIS[18] sensor.

The sample calculation results based on the MOD17A2/A3 algorithm are listed in **Table 2**. The NPPs for Asia Pacific, South America, and Europe, relative to North America, are shown in **Figure 17**. The phenomenal net ecosystem productivity of Asia Pacific is 4.2 larger than that of North America. The South American ecosystems deliver 2.7 times more than their North American counterparts, and Europe just 0.85. It is no surprise then that the World Bank[19], as well as agribusiness and logging companies – Archer Daniel Midlands (ADM), Bunge, Cargill, Monsanto, CFBC, Safbois, Sodefor, ITB, Trans-M, and many others – all have moved in force to plunder the most productive tropical regions of the world, see **Figure 18**.

The final result of this global "end-game" of ecological destruction will be an unmitigated and lightening-fast collapse of ecosystems protecting a large portion of humanity.[20]

Table 2: Version 4.8 NPP/GPP global sums (posted: 01 Feb 2007)[a]

Year[b]	GPP (Pg C/yr[c])	NPP[d] (Pg C/yr)
2000	111	53
2001	111	53
2002	107	51
2003	108	51
2004	109	52
2005	108	51

[a]Numerical Terradynamic Simulation Group, The University of Montana, Missoula, MT 59812, images.ntsg.umt.edu/index.php.
[b]2000 and 2001 were La Niña years, and 2002 and 2003 were weak El Niño years.
[c]1 Pg C = 1 peta gram of carbon = 10^{15} grams = 1 billion tonnes = 1 Gt of carbon. 50 Gt of carbon per year is equivalent to 1800 EJ yr^{-1}.
[d]This represents all above-ground production of living plants and their roots. Humans cannot dig up all the roots on the Earth, so effectively ∼1/2 NPP might be available to humans *if* all other heterotrophs living on the Earth stopped eating.

[18]MODIS (or Moderate Resolution Imaging Spectroradiometer) is a key instrument aboard the Aqua and Terra satellites. The MODIS instrument provides high radiometric sensitivity (12 bit) in 36 spectral bands ranging in wavelength from 0.4 to 14.4 μm. MODIS provides global maps of several land surface characteristics, including surface reflectance, albedo (the percent of total solar energy that is reflected back from the surface), land surface temperature, and vegetation indices. Vegetation indices tell scientists how densely or sparsely vegetated a region is and help them to determine how much of the sunlight that could be used for photosynthesis is being absorbed by the vegetation. Source: modis.gsfc.nasa.gov/about/media/modis_brochure.pdf.

[19]Source: (Anonymous, 2007). The World Bank through its huge loans is behind the largest-ever destruction of tropical forest in the equatorial Africa.

[20]For example, in the next 20 years, Australia may gain another 100 million refugees from the depleted Indonesia; look at Haiti for the clues.

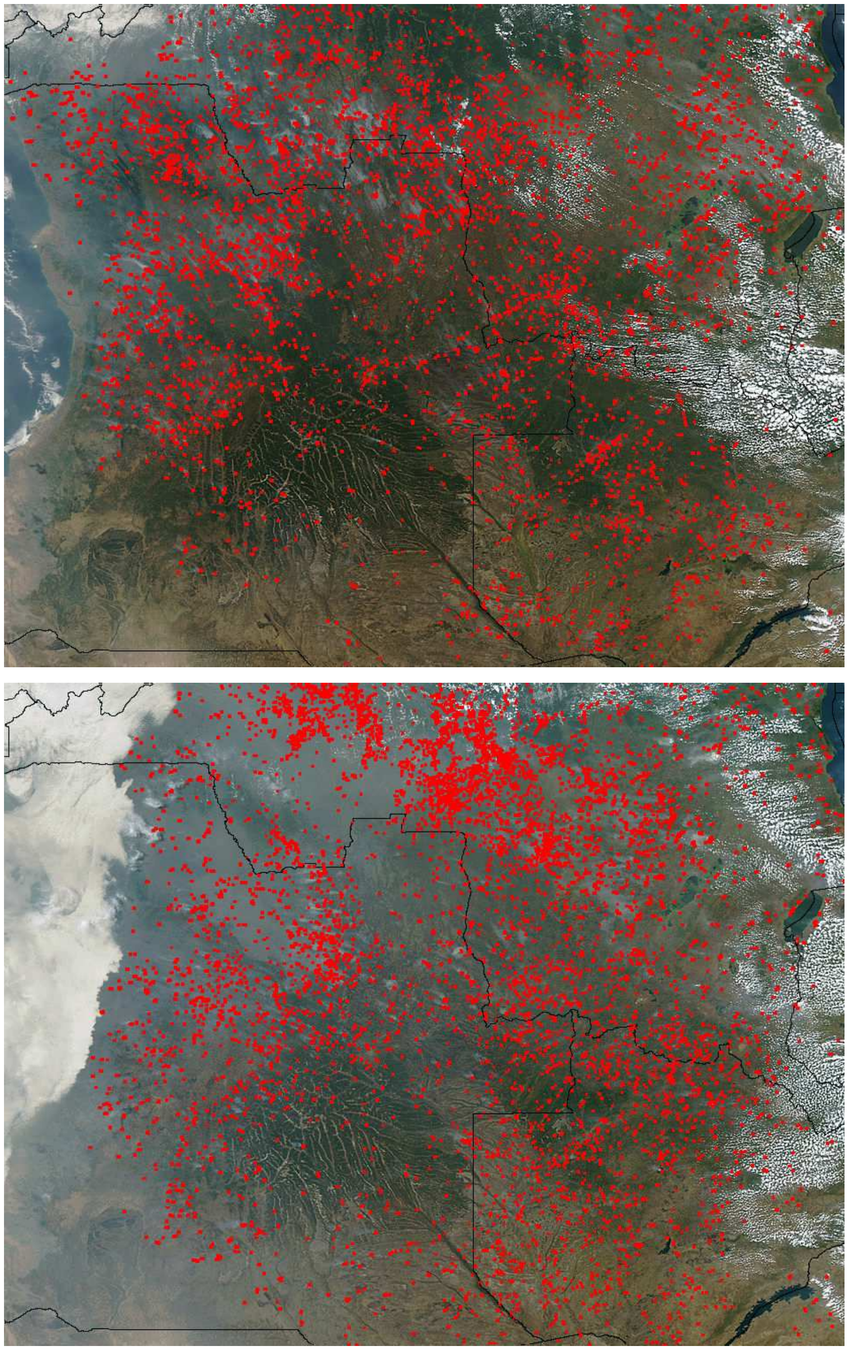

Figure 18: Hundreds of fires were burning in the Democratic Republic of Congo and Angola on Dec 16, 2005 (top), and Aug 11, 2006 (bottom). Most of the fires are set by humans to clear land for farming, rangelands, and industrial biomass plantations. In this way, vast areas of the continent are being irreversibly transformed. Source: Satellite Aqua, 2 km pixels size. Images courtesy MODIS Land Rapid Response Team at NASA.

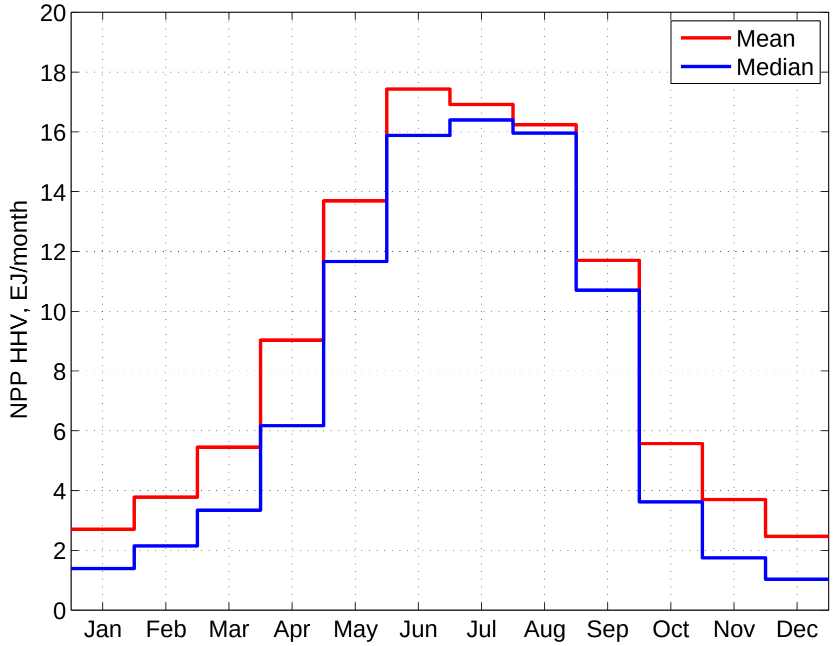

Figure 19: A MOD17A2/A3-based calculation of US NPP in the year 2003. Monthly data for the mean and median GPP were acquired from images.ntsg.umt.edu/browse.php. The land area of the 48 contiguous states plus the District of Columbia = 7444068 km^2. Conversion to higher heating values (HHV) was performed assuming 17 MJ kg^{-1} dmb biomass. Conversion from kg C to kg biomass was 2.2, see Footnote b in Table 10 in Appendix C. NPP = 0.47 × GPP for 2003. The robust *median* productivity estimate of the 2003 US NPP is 90 EJ yr^{-1}.

7.5 NPP in the US

The overall median values of net primary productivity may be converted to the higher heating value (HHV) of NPP in the US, see **Figure 19**. In 2003, thus estimated net annual biomass production in the US was 5.3 Gt and its HHV was 90 EJ. One must be careful, however, because the underlying distributions of ecosystem productivity are different for each ecosystem and highly asymmetric. Therefore, lumping them together and using just one median value can lead to a substantial systematic error. For example, the lumped value of US NPP of 90 EJ, underestimates the overall 2003 estimate[21] of $0.408 \times 7444068 \times 10^6 \times 17 \times 10^6 \times 2.2 \times 10^{-18} = 113$ EJ by some 20%.

To limit this error, one can perform a more detailed calculation based on the 16 classes of land cover listed in Table 2 in (Hurtt et al., 2001). The MODIS-derived median NPPs are reported for most of these classes. The calculation inputs are shown in **Table 3**. Since the spatial set of land-cover classes cannot be easily mapped onto the administrative set of USDA classes of cropland, woodland, pastureland/rangeland, and forests, Hurtt et al. (2001) provide an approximate linear mapping between these two sets, in the form of a 16 × 4 matrix of coefficients between 0 and 1. I have lumped the land-cover classes somewhat differently (to be closer to USDA's classes), and the results are shown in **Table 4** and **Figure 20**.

The Cropland + Mosaic class here comprises the USDA's cropland, woodland, and some of the pasture classes. The Remote Vegetation class comprises some of the USDA's rangeland and pastureland classes. The USDA forest class is somewhat larger than here, as some of the smaller patches of forest, such as parks, etc., are in the Mosaic class. Thus calculated 2003 US NPP is 118 EJ yr^{-1}, 74 EJ yr^{-1} of above-ground (AG) plant construction and 44 EJ yr^{-1} in root construction. In addition 12/74 = 17% of AG vegetation is in remote areas, not counting

[21]The median 2003 US NPP of 0.408 kg C m^{-2} yr^{-1} was posted at images.ntsg.umt.edu/browse.php.

Table 3: The 2003 US NPP by ground cover class

	Class[a]	Area[a] 10^6 ha	2003 US NPP[b] 10^6 t ha^{-1} yr^{-1}	Root:shoot[c]
1	Cropland+Mosaic[d]	219	893	0.318
2	Grassland	123	603	4.224
3	Mixed forest	38	1159	0.456
4	Woody savannah[e]	33	1694	0.642
5	Open shrubland[f]	124	620	1.063
6	Closed shrubland[g]	3	966	1.063
7	Deciduous broadleaf forest	95	1153	0.456
8	Evergreen needleleaf forest	118	1153	0.403

[a]Table 2 in (Hurtt et al., 2001).
[b]Numerical Terradynamic Simulation Group, The University of Montana, Missoula, MT 59812, images.ntsg.umt.edu/index.php.
[c]Table 2 in (Mokany et al., 2006).
[d]Lands with a mosaic of croplands, forests, shrublands and grasslands in which no one component covers more than 60% of the landscape.
[e]Herbaceous and other understory systems with forest canopy cover over 30 and 60%.
[f]Woody vegetation with less than 2 m tall and with shrub cover 10 to 60%.
[g]Woody vegetation with less than 2 m tall and with shrub cover > 60%.

Table 4: The 2003 US NPP by lumped ground cover classes

	Class[a]	Area[a] 10^6 ha	2003 US NPP[b] 10^6 t ha^{-1} yr^{-1}	HHV[c] EJ yr^{-1}
1	Cropland+Mosaic	219	1484.8	25.2
2	Pastures	123	142.3	2.4
3	Remote vegetation[d]	160	724.1	12.3
4	Forest[e]	252	2030.0	34.5
5	Roots[f]	754	2575.0	43.8

[a]Derived from Table 2 in (Hurtt et al., 2001) and USDA classes
[b]In classes 1 – 4, only above-ground biomass is reported. Class 5 lumps all the roots. The calculations here are based on Table 3 with the multiplier of 2.2 to convert from carbon to biomass.
[c] The higher heating value with 17 MJ kg^{-1} on the average.
[d] Classes $4 + 5 + 6$ in Table 3.
[e]Classes $3 + 7 + 8$ in Table 3.
[f]Note that roots comprise $44/74 = 59\%$ of NPP. Also the land cover classes here account for 97% of US land area.

the remote forested areas. Note that my use of land-cover classes and their typical root-to-shoot ratios yields an overall result (118 EJ yr^{-1}) which is very similar to that derived by the Numerical Terradynamic Simulation Group (113 EJ yr^{-1}).

Therefore, the DOE/USDA proposal to produce 130 billion gallons of ethanol from 1400 million tonnes of biomass (Perlack et al., 2005) each year – and year-after-year –, would consume 32% of the remaining above-ground NPP in the US, see **Figure 20**, if one assumes a 52% energy-efficiency of the conversion.[22] At the current 26% overall efficiency of the corn-ethanol cycle

[22]As I mentioned before, this efficiency is close to the *theoretical* thermodynamic efficiency of the Fischer-Tropsch process *never* practically achieved with coal, let alone biomass. After 87 years of research and produc-

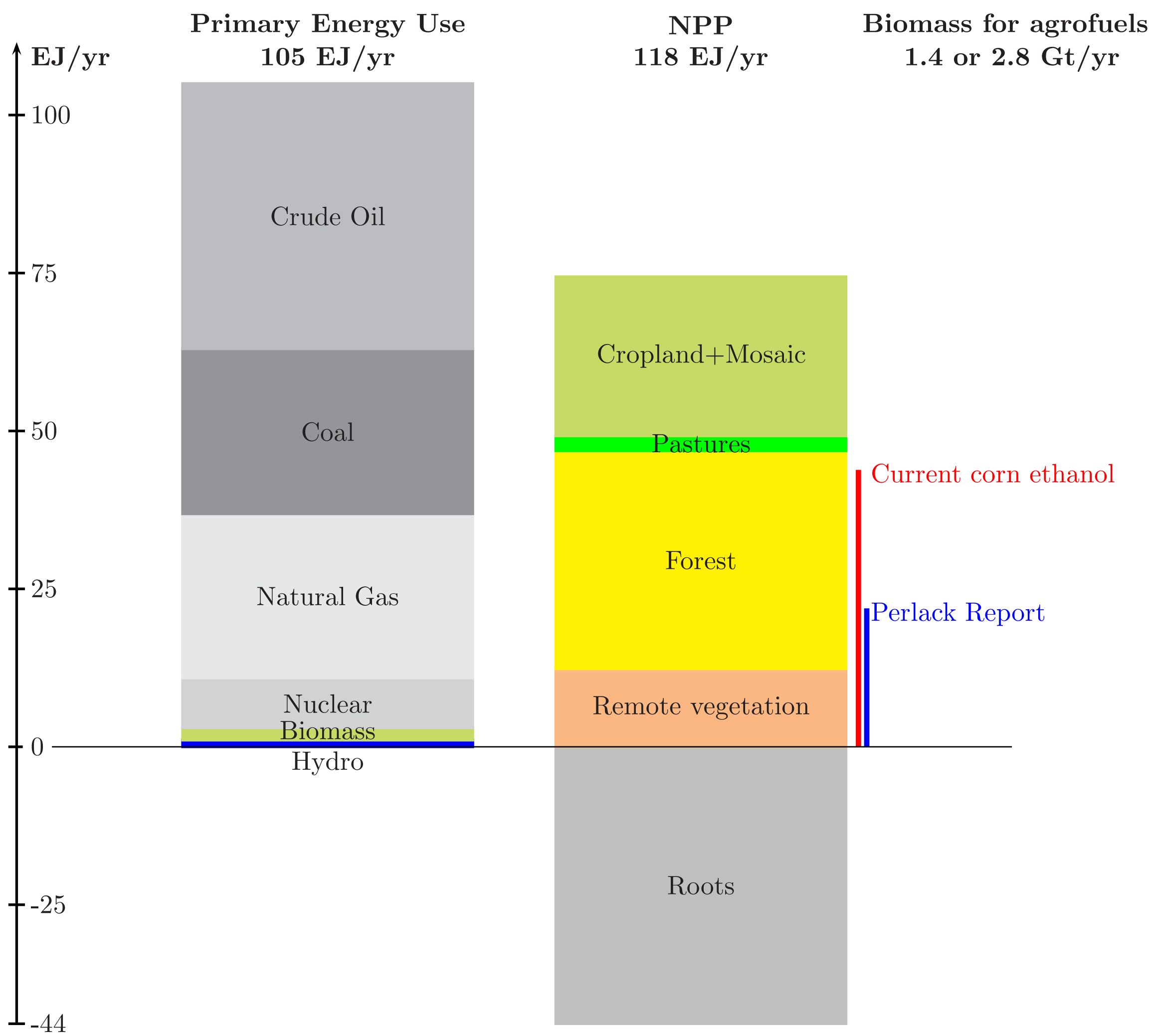

Figure 20: Primary energy consumption and net primary productivity (NPP) in the US in 2003. The annual growth of all biomass in the 48 contiguous states plus the District of Columbia has been translated from gigatonnes per year to the higher heating value of this biomass growth in exajoules per year. The USDA/DOE proposal (Perlack et al., 2005) to produce 130 billion gallons of ethanol per year from 1.4 billion tonnes of biomass would consume 32% of above-ground NPP in the US at a 52% conversion efficiency, or 64% at the current efficiency of the corn-ethanol cycle (Patzek, 2006a). Sources: EIA, Numerical Terradynamic Simulation Group, and (Patzek, 2007).

(Patzek, 2006a), roughly 64% of all AG NPP in the US would have to be consumed to achieve this goal with zero harvest losses.[23] To use more than half of all accessible above-ground plant growth in all forests, rangeland, pastureland and agriculture in the US to produce agrofuels would be a continental-scale ecologic and economic disaster of biblical proportions.[24]

tion experience, current F-T coal plants achieve a 42% efficiency, see, e.g., (Steynberg and Nel, 2004).

[23]In forestry, roughly 1/2 of AG biomass is exported as tree logs; the rest is lost and burned.

[24]We are moving swiftly down this merry path: "Green Energy Resources traveled to Florida and Georgia this week to procure upwards of a million tons of forest fire timber from the region at no cost to the company. The timber is valued at approximately $15-20 million. Green Energy Resources plans to use the wood to supply biomass power plants in the United States as well as for exports." Source: Green Energy Resources, May 23, 2007, Press Release. Accessed on June 21, 2007.

8 Photovoltaic Cells vs. Agrofuels

It seems that we will do anything to keep on driving our cars. Therefore, the proper question to ask is this: How much continuous motive power can be extracted from 1 m^2 of land surface occupied by photovoltaic cells, wind turbines, or major energy crops: corn, sugarcane, acacias, and eucalypts? For comparison, I also use 1 m^2 of land overlying a medium-quality oil field produced at a constant rate to deliver automotive fuels. For each renewable energy source, I calculate an extra land area necessary to recover all free-energy costs of producing an automotive fuel or electricity. Similarly, I charge the oil field with all energy costs of recovering oil, transporting it to refineries, processing to gasoline and/or diesel fuel, and transporting the finished automotive fuels from the refineries to service stations.[25] I spend the generated automotive power on driving an efficient internal-combustion engine car, such as the Toyota Prius or a diesel engine car, and an all-electric battery car.

8.1 General Comparisons

I start from the ancient solar energy stored in a medium-to-good quality oil reservoir. I assume that this reservoir is produced at a constant average rate over 20 – 30 years and 100 $W\,m^{-2}$ of primary power is drawn from it continuously. This amount of power is rather small compared with prolific oil fields, which can develop 200 to 400 $W\,m^{-2}$ for years. The only problem with my oil reservoir is that *this resource is finite and irreplaceable* and after 30 years there is *no* producible oil left in it.

One m^2 of horizontal photovoltaic cell panels may generate 15% of the average[26] US insolation of 200 W, i.e., 30 W of electricity continuously.[27] I also assume that photovoltaic cell assemblies effectively occupy twice the area of the panels.

One m^2 of land occupied by wind turbines may produce continuously 1 W of electricity (Hayden, 2002).

One m^2 of land occupied by agrofuel plantations may produce continuously 0.07 to 0.40 $W\,m^{-2}$ as transportation fuels. All systems are compared in **Figure 21**. Only the renewable systems are compared in **Figure 22**.

8.2 US corn-ethanol system

The Second Law analysis of the US corn-ethanol system is based on the calculations summarized in **Figure 23** and **Table 5** (Patzek, 2004). The average corn grain harvest was assumed to be 8600 $kg\,ha^{-1}$, below the all-time record yield of 10000 $kg\,ha^{-1}$ in 2004. The ethanol plants were assumed to operate at 92% of theoretical efficiency. The *net-free energy ratio*[28] of the US corn grain-ethanol system is $0.24/(0.13 + 0.19) = 0.77$, see Table 5. Notice that the Second Law analysis here cannot be translated into an equivalent net-energy ratio used in the nonphysical and incomplete analyses by DOE and USDA (see Patzek (2006a) for more information).

8.3 Acacia-for-energy system

The exceptionally prolific stand of *Acacia mangium* trees in **Figure 24**, captures solar energy at the rate of 1.39 W/m^2 as stemwood+bark, and 0.31 W/m^2 as slash, which is usually destroyed by burning. Twenty percent of the stemwood mass is lost in harvest, handling, and processing. Again, we do not want to just burn the wood, but we convert its free energy to electricity and/or automotive fuels. For the three scenarios discussed in Patzek & Pimentel (2006),

[25] The substantial fuel transportation and blending costs are *not* included for biofuels.

[26] The 24-hour, 365-day average insolation of a flat horizontal surface anywhere in the US varies between 125 and 375 $W\,m^{-2}$ (3 to 9 $kWh\ m^{-2}\ day^{-1}$), and is almost exactly 200 $W\,m^{-2}$ on the average.

[27] Of course free energy is also used to produce solar cells. The life-cycle analysis of solar cells will be performed later.

[28] An extension of the popular but inadequate measure of efficiency of energy systems (Patzek, 2006a).

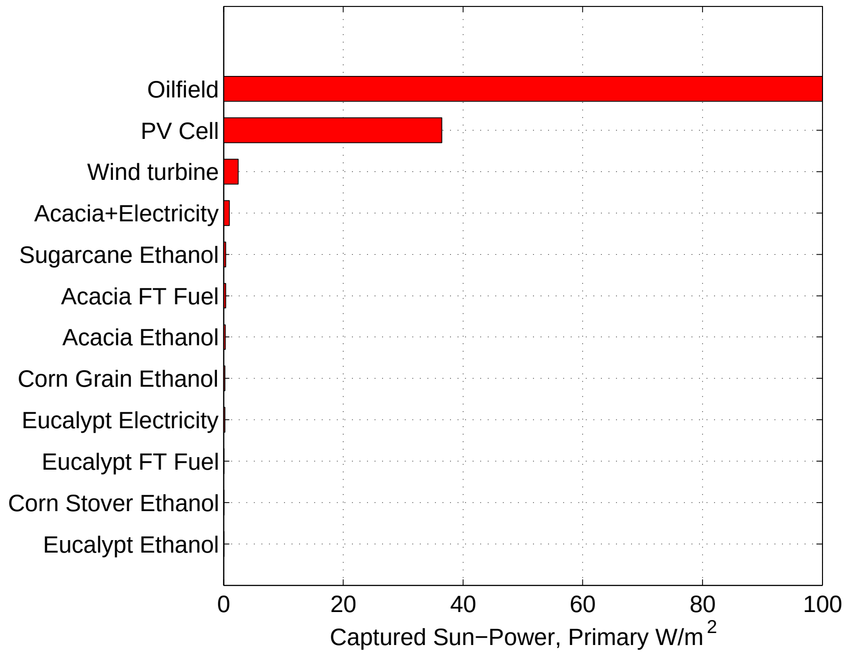

Figure 21: From the top: Ancient solar power extracted from 1 m^2 of a medium-quality oil reservoir by producing its crude oil for 30 years at a constant rate; continuous solar power captured by a 15 $\mathsf{W\,m}^{-2}$ horizontal photovoltaic cell panel converted to primary energy by multiplying it by 2.43 (the assumed ratio of efficiencies of an all-electric car to a 40 mpg IC car); continuous primary power of a 1 $\mathsf{W\,m}^{-2}$ wind turbine; continuous solar power captured by *A. mangium*, Brazilian sugarcane, US corn, and *E. deglupta* and converted to various primary energy sources, mostly agrofuels. Note that the specific amounts of power outputs of these plant-energy systems are almost invisible at this scale.

Table 5: Solar power capture, free energy consumption, and free energy output by US corn field-ethanol distillery systems (Patzek, 2004)

Quantity	Power	Units
Grain capture	0.44	W/m^2
Stem/leaves capture[a]	0.46	W/m^2
CExC[b] in corn production	0.13	W/m^2
CExC in ethanol production	0.19	W/m^2
Grain ethanol capture[c]	0.24	W/m^2
Stover Ethanol capture[c]	0.10	W/m^2
60%-efficient fuel cell output[d]	0.15	W_e/m^2
35%-efficient IC engine output	0.09	W/m^2

[a] Abbreviated as stover. 75% of corn stover is collected from the fields, a long-term environmental calamity.
[b] The cumulative free energy (exergy) consumption, CExC, is equal the minimum work of reversible restoration of the plantation ecosystem and its energy input sources.
[c] Only for comparison. Fuel exergy is *not* the useful work we compare here.
[d] See (Bossel, 2003; Patzek and Pimentel, 2006).

the amount of solar energy captured as electricity is 0.35 W/m^2; as the FT-diesel fuel + a 35%-efficient IC engine car (equivalent to a Toyota Prius) + electricity, 0.26 W/m^2; and as ethanol, 0.11 W/m^2. The negative free energy cost of pellet manufacturing is 0.41 W/m^2 (as much as sugarcane-ethanol manufacturing), and the plantation maintenance consumes about 0.1 W/m^2 (a bit less than the 0.14 W/m^2 to run a sugarcane plantation). The net solar power captured by this planation is negative, unless the free-energy cost of pellet manufacturing is cut in half.

Table 6: Solar power capture, free energy consumption, and free energy output by acacia and eucalypt plantation-energy systems (Patzek and Pimentel, 2006)

Quantity	Acacia	Eucalypt	Units
Stem capture	1.38	0.34	W/m^2
Slash[a] capture	0.31	0.19	W/m^2
Pellet capture	1.10	0.28	W/m^2
CExC[b] in pellet production	0.41	0.10	W/m^2
CExC in plantation	0.07	0.05	W/m^2
Electricity output	0.35	0.09	W_e/m^2
FT fuel output[c]	0.38	0.10	W/m^2
FT fuel+35% efficient IC engine output	0.13	0.03	W/m^2
FT electricity output	0.13	0.03	W_e/m^2
Ethanol fuel output[c]	0.30	0.07	W/m^2
Ethanol fuel+35% efficient car output	0.11	0.03	W/m^2

[a]This slash is no "trash" and should be left on the plantation to decompose.
[b]The cumulative exergy consumption, CExC, is equal the minimum work of reversible restoration of the plantation ecosystem and its energy input sources.
[c]Only for comparison. Fuel exergy is *not* the useful work we compare here.

8.4 Eucalyptus-for-energy system

The not-so-prolific stand of *Eucalyptus deglupta* in **Figure 25**, more representative of average plantations, captures 0.34 W/m^2 as stemwood+bark, 0.19 W/m^2 as slash. When this energy is converted to electricity, only 0.09 W/m^2 is captured. The FT-diesel fuel/car/electricity option captures 0.07 W/m^2. Finally, the ethanol/car option captures 0.03 W/m^2. The negative free energy of pellet production is 0.10 W/m^2, and the eucalypt plantation maintenance consumes

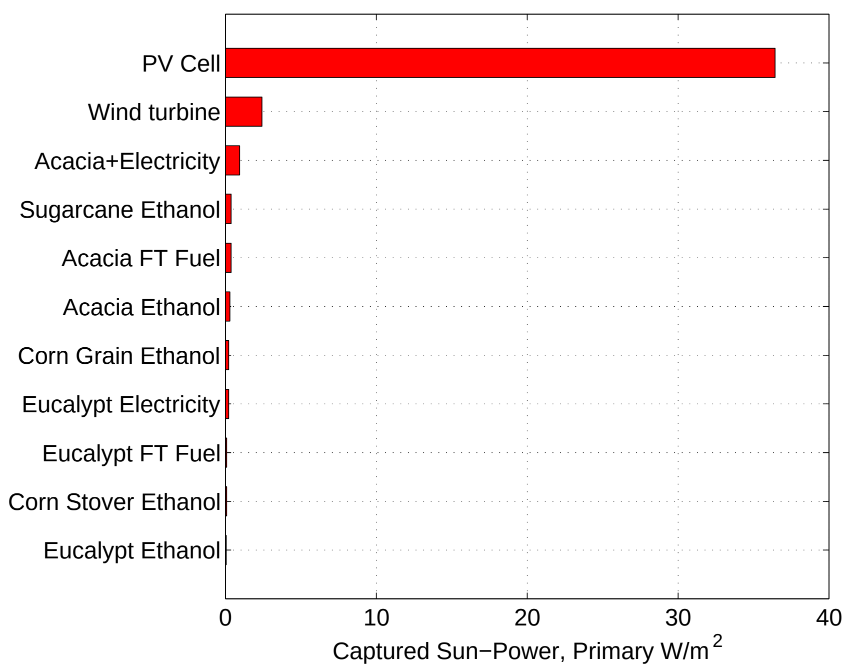

Figure 22: Primary continuous power delivered by renewable systems (crude oil has been excluded).

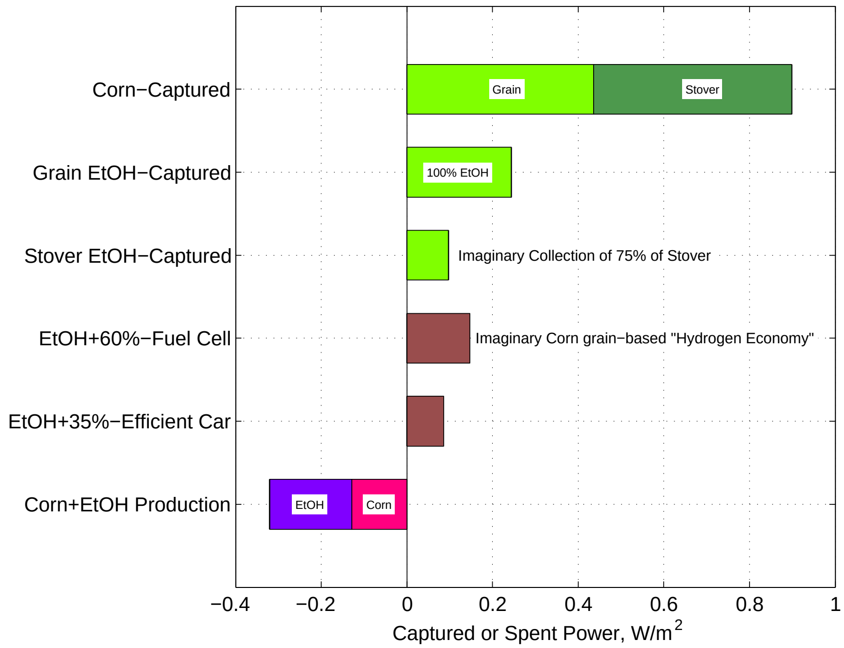

Figure 23: From the top: Solar power captured by 1 m^2 of an average US corn field as grain and stover; as grain ethanol in an average corn-starch refinery; as stover ethanol in an imaginary 75%-efficient lignocellulosic refinery; as an imaginary 60%-efficient fuel cell car (see (Bossel, 2003)); and as 35%-efficient internal combustion engine car. The negative free energy costs of producing corn and grain ethanol are also shown. The unknown free-energy costs of running an imaginary lignocellulosic stover refinery are set to zero. Note that the *motive* power of cars is coded with the dark brown color to distinguish it from the *chemical* power of ethanol or biomass.

0.05 W/m^2. It seems that the net solar power captured by the eucalypt planation is always negative, no matter what we do about wood pellets. For convenience, the acacia and eucalypt capture efficiencies are listed in **Table 6**.

8.5 Sugarcane-for-energy system

The prolific average sugarcane plantation in Brazil in **Figure 26**, captures 0.59 W/m^2 as stem sugar, 0.57 W/m^2 as bagasse, and 0.42 W/m^2 as "trash," both attached and detached. Because of the unique ability of satisfying the huge CExC in cane crushing, fermentation, and ethanol distillation (0.41 W/m^2), as well as fresh bagasse + "trash" drying (0.27 W/m^2), with the chemical exergy of bagasse and the attached "trash," sugarcane is the only industrial energy plant that may be called "sustainable." The sugarcane ethanol has the positive free energy balance when used with 60%-efficient fuel cells, a technology that still is in its infancy, and whose real efficiency of generating shaft work is 38%, see (Bossel, 2003; Patzek and Pimentel, 2006). The remainder of the "trash" must be left in the soil to decompose and improve the soil's structure. The free energy used to produce cane (0.14 W/m^2) and clean the distillery wastewater BOD (0.06 W/m^2) exceeds the benefits from a 35-% and 20%-efficient internal combustion engines (0.14 and 0.08 W/m^2, respectively). For convenience all these numbers are listed in **Table 7**.

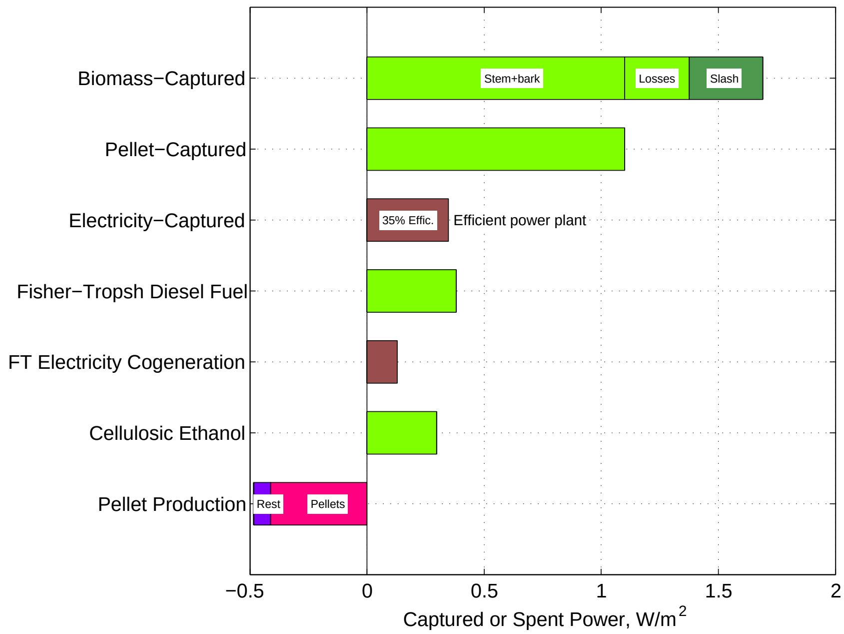

Figure 24: From the top: Solar power captured by 1 m^2 of the example *Acacia mangium* stand in Indonesia; as electricity generated from wood pellets in a 35%-efficient power plant; as FT-diesel fuel in a 35%-efficient internal combustion engine car, and electricity; and as ethanol from the pellets powering a 35%-efficient internal combustion engine car. The negative free energy costs of producing the acacia wood pellets and maintaining the plantation (Rest) are larger than our three options of generating useful shaft work from the captured solar energy. Note that the *motive* power of electricity is coded with the dark brown color to distinguish it from the *chemical* power of fuels.

Table 7: Solar power capture, free energy consumption, and free energy output by Brazilian sugarcane-ethanol system (Patzek and Pimentel, 2006)

Quantity	Power	Units
Stem sugar capture	0.59	W/m^2
Dry bagasse capture	0.57	W/m^2
Dry attached “trash” capture[a]	0.15	W/m^2
Dry mill “trash” capture	0.27	W/m^2
Ethanol capture	0.41	W/m^2
Extra electricity capture	7.7×10^{-5}	W$_e$/m^2
CExC[b] in cane production	0.14	W/m^2
CExC in ethanol production	0.41	W/m^2
CExC in bagasse and trash drying	0.30	W/m^2
CExC in BOD removal	0.06	W/m^2
20%-efficient IC engine output	0.08	W/m^2
35%-efficient IC engine output	0.14	W/m^2
60%-efficient fuel cell output[c]	0.25	W/m^2

[a]The detached “trash” $> 1/2$ of the total must be left in the soil to decompose.
[b]See (Patzek and Pimentel, 2006).
[c]Patzek & Pimentel (2006) show that the 60%-efficient fuel cells do not exist, and their real efficiency is just above that of a 35%-efficient internal combustion engine, or a hybrid/diesel car.

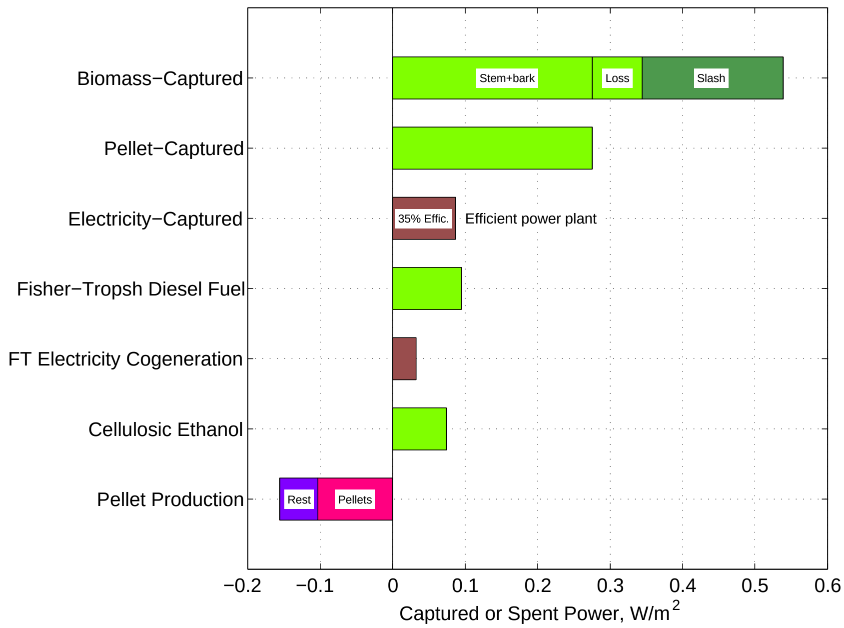

Figure 25: From the top: Solar power captured by 1 m^2 of the example *Eucalyptus deglupta* stand in Indonesia; as electricity generated from wood pellets; as FT-diesel fuel in a 35%-efficient internal combustion engine car, and electricity; and as ethanol from the pellets powering a 35%-efficient internal combustion engine car. The negative free energy costs of producing the eucalypt wood pellets and maintaining the plantation (Rest) are larger than our three options of generating useful shaft work from the captured solar energy. Note that the *motive* power of electricity is coded with the dark brown color to distinguish it from the *chemical* power of fuels.

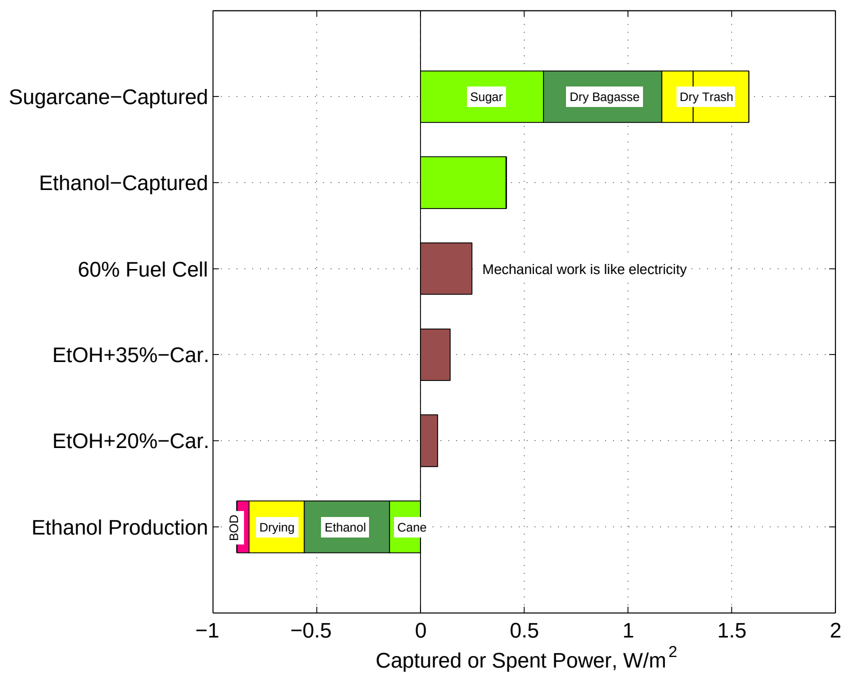

Figure 26: From the top: Solar power captured by 1 m^2 of the average sugarcane plantation in Brazil: as the chemical exergies of sugar, bagasse, and "trash;" as the chemical exergy of ethanol; as electricity from an imaginary 60%-efficient fuel cell (Bossel, 2003); as shaft work from a 35%-; and 25%-efficient internal combustion engine cars. The negative free energy costs of producing the sugarcane (Cane) and cleaning up the distillery wastewater (BOD) are larger than both internal combustion engine options, but smaller than the fuel cell option. The negative costs of ethanol distillation (Ethanol), and bagasse + "trash" drying (Drying), are paid with the chemical exergies of bagasse and attached "trash" (the left part of the rightmost bar segment at the top). Note that the *motive* power of cars is coded with the dark brown color to distinguish it from the *chemical* power of fuels.

8.6 Driving on Solar Power

In addition to the 1 m^2 of land surface used in the comparisons above to generate motive power, additional land area is needed to recover the energy and environmental costs of the power generation. This additional fractional area is calculated as follows

$$\delta A = \frac{\sum \mathsf{CExC} \text{ in all activities}}{\text{Solar power captured as biomass}} \qquad \frac{\mathsf{m}^2}{\mathsf{m}^2} \tag{4}$$

where CExC denotes the cumulative rate of exergy consumption in all activities related to power generation (or the minimal restoration work).

The total specific area necessary to generate the motive power is now

$$1 + \delta A \qquad \mathsf{m}^2 \tag{5}$$

To calculate how much total area of an energy system is needed to drive a single car, I make the following assumptions:

1. Assume driving 24000 $\mathsf{km\ yr}^{-1}$ (15000 $\mathsf{miles\ yr}^{-1}$) at 5.9 $\mathsf{L\ (100\ km)}^{-1}$ (40 $\mathsf{miles\ gal}^{-1}$) in a hybrid car similar to a Honda Civic VX or Toyota Prius, or a diesel engine car. The fuels used are corn-, sugarcane- or "cellulosic"-ethanol, or agrodiesel.

2. Alternatively, drive an all-electric car that is $0.85/0.35 = 2.43$ times more efficient than the hybrid.

3. Account for average energy costs of producing gasoline from crude oil (17%) (Patzek, 2006a) and agrofuels from biomass as in Tables 5 to 7.

4. Assume that an average solar photovoltaic panel sequesters 15% of insolation (30 $\mathsf{W\ m}^{-2}$ on the 24-hour, annual average) and operates for 30 years. Assume that access areas, roads, and energy losses double the minimum land area occupied by the panels, halving their capture efficiency to 15 $\mathsf{W\ m}^{-2}$.

5. Assume that an average wind turbine delivers 1 $\mathsf{W\ m}^{-2}$ continuously (see, e.g., Hayden (2002)).

6. Since photovoltaic cells and wind turbines are used to power the all-electrical cars, convert their electrical outputs to primary energy by multiplying their ratings by 2.43.

7. Assume energy costs of manufacturing and deploying PV panels and wind turbines, 33% and 10% of their 30-year energy production.

8.6.1 Calculation Results

The fractional land areas needed to restore the free energy costs of power generation from 1 m^2 of land area were calculated from Eqs. (4) and (5), and Tables 5 – 7. The results are shown in **Figure 27**.

The net and gross ratios of land area needed to develop the motive power and pay for the free-energy costs of power generation are listed in **Table 8**, and displayed in **Figures 28** and **29**.

Notice that the plots in Figures 28 and 29 are semilogarithmic and the plotted areas increase by a factor of 10^4 from left to right. For example, for each 1 m^2 of medium-quality oil fields one needs 620 m^2 of corn fields to replace gasoline with corn ethanol and pay for the free energy costs of the ethanol production. Similarly, one can drive our example cars for one year from $\sim$30 m^2 of oil fields, 90 m^2 of photovoltaic cells, 1100 m^2 of wind turbines, and $\sim$18000 m^2 of corn fields, see Table 8 and Figure 29.

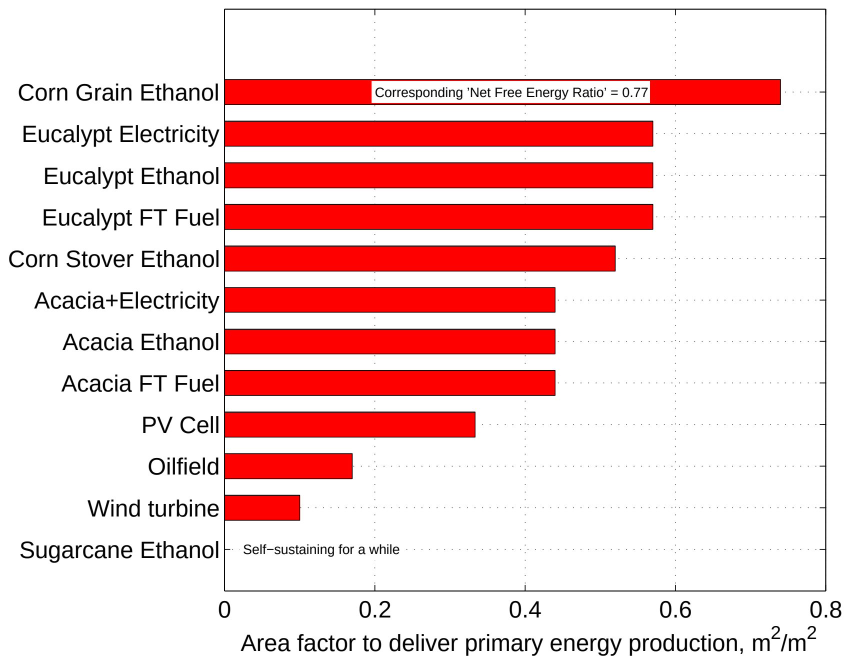

Figure 27: Fractional land area needed to restore free-energy costs of power generation from 1 m^2 of land occupied by the different energy-production systems.

Table 8: Ratios of land areas needed to power cars described in Section 8.6 using different motive power sources

Technology	Net Ratio[a]	Gross Ratio[b]
Oilfield	1.0	1.0
PV Cell	2.7	3.0
Wind turbine[c]	40	37
Acacia+Electricity	102	125
Sugarcane Ethanol[d]	250.0	214
Acacia FT Fuel	263	324
Acacia Cellulosic Ethanol	333	410
Eucalypt Electricity	417	593
Corn Grain Ethanol	442	620
Corn Stover Cellulosic Ethanol	1000	1299
Eucalypt FT Fuel	1000	1342
Eucalypt Cellulosic Ethanol	1427	1917

[a]Ratio of the land area needed to develop the needed motive power to the equivalent oilfield area.
[b]Ratio of the land area needed to develop the needed motive power and restore the power-generation free energy costs to the equivalent oilfield area.
[c]Energy fraction that goes into constructing a wind turbine (0.10 of its output) is less than the energy fraction of crude oil used to produce gasoline (0.17).
[d] Energetically, sugarcane is self-sustaining until soil is eroded away and/or depleted of nutrients.

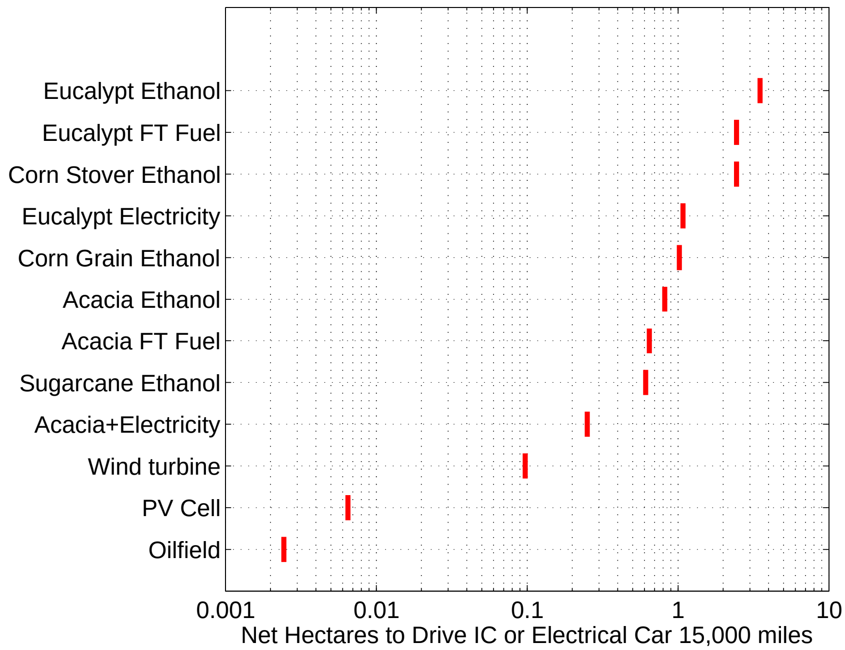

Figure 28: The net area of land needed just to power an efficient (40 mpg) IC engine car or an all-electric car equivalent to 100 mpg, and drive it 15000 miles per year. Note that the plot's x-axis is logarithmic and the area increases by a factor of 10000 from left to right.

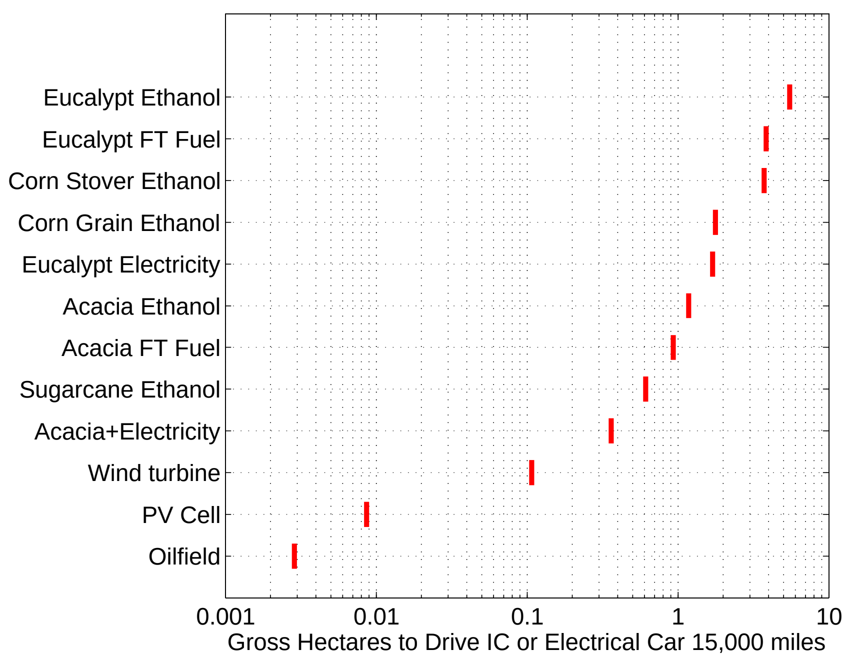

Figure 29: The total area of land needed to power an efficient (40 mpg) IC engine car or an all-electric car equivalent to 100 mpg, and drive it 15000 miles per year. Most of the free energy costs of fuels, fertilizers, and some environmental costs of power generation are accounted for. Note that the plot's x-axis is logarithmic and the area increases by a factor of 10000 from left to right.

9 Conclusions

In this paper I have painted a radical vision of a world in which fossil fuels and agrofuels will be used increasingly less in transportation vehicles. Gradually, these fuels will be replaced by electricity stored in the vehicle batteries. With time the batteries will get better, and electric motors will take over powering the vehicles. The sources of electricity for the batteries will be increasingly solar photovoltaic cells and wind turbines. The vagaries of cloudy skies and irregular winds will be alleviated to a large degree by the surplus batteries being recharged and shared locally, with no transmission lines out of a neighborhood or city.

I have shown that even mediocre solar cells that cost 1/3 of their life-time electricity production to be manufactured are at least 100 times more efficient than the current major agrofuel systems. When deployed these cells will not burn forests; kill living things on land, in the air, and in the oceans; erode soil; contaminate water; and emit astronomic quantities of greenhouse gases. Unlike agrofuels, the solar cells will not take away food and environment from the largest part of the human population in the tropics, and they will not contribute to untold corruption, human misery, squalor, and slave labor. Each hectare of solar cells will *replace* 70, all the way up to 650 hectares of fields and tree plantations. This means significant opportunities to store atmospheric carbon in tree and other plant mass for the next two- or three hundred years. Finally, by the time we will have to replace the early generations of solar cells in 30 to 40 years, many of the current agrofuel systems will be degraded ecological deserts with displaced human populations.

I have also shown you that the Earth simply cannot produce the vast quantities of biomass we want to use to prolong our unsustainable lifestyles, while slowly committing suicide as a global human civilization.

In passing, I have noted that the "cellulosic biomass" refineries are very inefficient, currently impossible to scale, and incapable of ever catching up with the runaway need to feed one billion gasoline- and diesel-powered cars and trucks.

Finally, no future transportation system will allow complete "freedom of personal transportation" for everyone. I suggest that good public transportation systems will free many, if not most people *from* personal transportation.

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The opinions expressed in this paper are those of the author, who is solely responsible for its content and any errors or omissions.

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A Ecosystem Definition and Properties

As shown in **Figure 9**, the *autotrophic*[29] plants capture CO_2 from the atmosphere, and water and dissolved nutrients[30] from soil. Using solar light, plants convert all these chemical inputs into biomass through *photosynthesis*, see **Figure 30**.

Plants are food to the plant-eating *heterotrophs*:[31] animals, fungi, and bacteria. All die in place and their bodies are recycled for nutrients. Heterotrophs consist of consumers and decomposers. Consumers eat mostly living tissues. Decomposers consume dead organic matter and mineralize[32] it.

Definition 1 An ecosystem (an earth household) is a community of living organisms that interact with their non living physical environment (habitat). Most elements of an ecosystem are thoroughly connected (Lovelock, 1979; Lovelock, 1988; Capra, 1996), but over limited spacial scales.[33] In addition to solar energy and inorganic matter, the three basic structural and functional components of an ecosystem are autotrophs, heterotrophs and dead organic matter. □

Inputs to an ecosystem are biotic[34] and abiotic:

1. Abiotic inputs are solar energy, the atmospheric gases (CO_2, O_2, N_2, NO_x and SO_x), mineral nutrients in the soil, rain, surface water, and groundwater.
2. Biotic inputs are organisms that move into the ecosystem, but also organic compounds: proteins, lipids, carbohydrates, humic acid, etc.

Some dead organisms are buried in swamps, lakes, shallow coastal waters, etc., see **Figure 15**, and some nutrients are imported with floods and rain, while some are exported by rivers and wind. A vast majority of the biomass is, however, recycled within the boundaries of the mother ecosystem[35] in agreement with the Second Law of thermodynamics. This way, a buffalo might eat a wolf, whose bones were incorporated as phosphorous in the prairie grass.

Ecosystems change with time, organisms live and die, and move in and out. Ecosystems are subject to many disturbances: floods, fire, storms, droughts, invasions, and so on.

[29]From Greek *autotrophos* supplying one's own food (Webster, 1993).

[30]Water-soluble chemical compounds rich in N, P, K, Ca, Mg, S, Fe, etc.

[31]Requiring complex organic compounds of nitrogen, phosphorous, sulfur, etc., and carbon (as that obtained from plant or animal matter) for metabolic synthesis (Webster, 1993).

[32]For example, nitrogen can be transformed into inorganic molecules assimilable by plants, such as the aqueous ammonium or nitrate ions, as well as nitrogen dioxide, by (1) microbial *fixation* of the atmospheric N_2 and (2) by microbial *mineralization* of organic nitrogen in soil. Conversely, soil nitrogen is returned back to the atmosphere through microbial *denitrification*. The opposite process, oxidation of dissolved ammonia to nitrite and nitrate, is called *nitrification*. For details, see Smil (1985).

[33]In order for an ecosystem to be stable and its emerging properties at a larger scale be independent of the structural details of the smaller scales, the covariances of everything must decline at least exponentially with distance scaled by a yardstick characteristic of the smaller scales.

[34]Of, relating to, or caused by living organisms (Webster, 1993).

[35]Most ecosystems do not have distinct natural boundaries. Boundaries chosen by us in most cases are arbitrary subdivisions of a continuous gradation of communities.

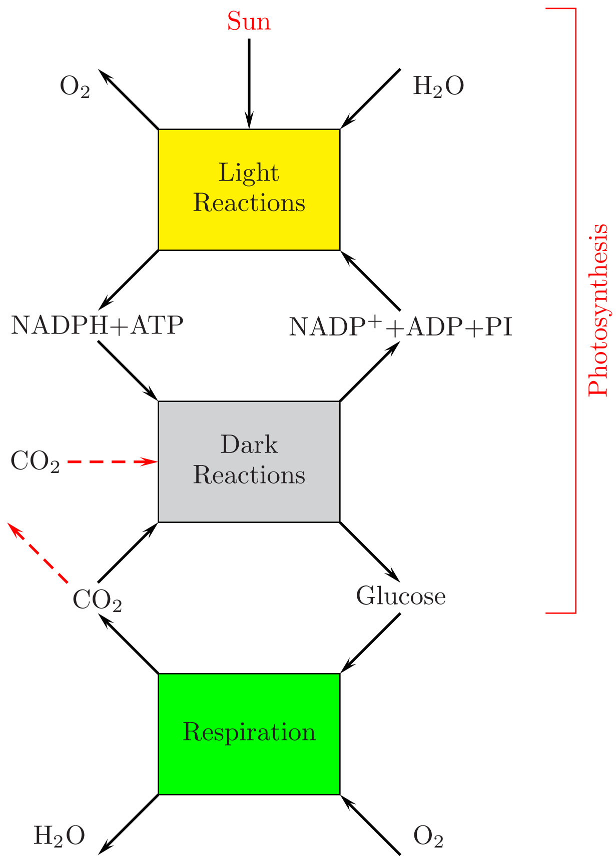

Figure 30: The light reactions use photons to strip protons from water and store energy in NADPH (nicotinamide adenine dinucleotide phosphate) and ATP (adenosine 5′-triphosphate nucleotide). Both these molecules are used to reduce CO_2 and combine carbon with hydrogen and phosphate in the Calvin Cycle or dark reactions: $3\ CO_2 + 9\ \mathsf{ATP} + 6\ \mathsf{NADPH} \rightarrow$ glyceraldehyde-3-phosphate $+ 9\ \mathsf{ADP} + 8\ \mathsf{PI} + 6\ \mathsf{NADP}^+$. Here ADP is adenosine diphosphate, PI is inorganic phosphate, and NADP^+ is the oxidized form of NADPH. Glyceraldehyde-3-phosphate may be converted to other carbohydrates such as metabolites (fructose-6-phosphate and glucose-1-phosphate), energy stores (sucrose or starch), or cell-wall constituents (cellulose and hemicelluloses). By respiring plants consume O_2 and convert their energy stores back to CO_2 and water.

B Mass Balance of Carbon in an Ecosystem

An eco-*system* is a *system* known to thermodynamics only if a three-dimensional surface[36] fully enveloping the system's contents is imagined for the life-span of the ecosystem. Of course, this surface may itself be time-dependent, but not right now.

Once there is a boundary, the carbon mass accumulation *in* the ecosystem is defined through the carbon mass flow *crossing* its boundary, and the *interior* carbon sources and sinks. The general mass-balance equation that describes all physical systems, (see, e.g., Bird et al. (1960)), can be written for carbon in the following way:

$$\underbrace{\frac{\mathrm{d}C}{\mathrm{d}t}}_{\substack{\text{Rate of living}\\ \text{carbon}\\ \text{accumulation}}} = \underbrace{-\oint_{\text{Boundary}} \boldsymbol{\mathcal{F}} \cdot \boldsymbol{n} dA}_{\substack{\text{Net rate of}\\ \text{carbon}\\ \text{flow out}}} \underbrace{+\sum \text{Sources} - \sum \text{Sinks}}_{\substack{\text{Net rate of}\\ \text{carbon}\\ \text{production inside}}} \quad \mathsf{kg\ C\ s^{-1}} \tag{6}$$

Here $\boldsymbol{\mathcal{F}}$ is the overall carbon flux vector, $\boldsymbol{n}$ is the unit outward normal to the system boundary, and the summation (integral) is over the entire system boundary. The sources *inside* the system volume are the photosynthesizing autotrophs, and the sinks are the respiring autotrophs and heterotrophs, fires, soil carbon oxidation, volatile hydrocarbon production, etc. The overall carbon flux $\boldsymbol{\mathcal{F}}$ is the vector sum of several different mechanisms of carbon mass exchange, such as convection with air, convection with moving heterotrophs, convection with soil-, river- and flood water, convection with eroded soil, etc. Each of the particular fluxes is nonzero over those parts of the system boundary where it operates and zero elsewhere.

Let's define $\dot{m}_i$, the overall outward carbon mass flow rate due to a specific flux i; Gross Primary Production (GPP), the sum of autotroph photosynthesis sources; R_a, the overall autotroph respiration sink; R_h, the overall heterotroph respiration sink; R_f, the overall fire sink; R_v, the overall volatile hydrocarbon production sink; R_s, the soil carbon oxidation sink; R_b, the carbon burial sink; etc.

$$\begin{aligned} \dot{m}_i &= \oint_{\text{Boundary}} \boldsymbol{\mathcal{F}_i} \cdot \boldsymbol{n} dA \\ \mathsf{GPP} &= \sum \text{Sources} \\ R &= R_a + R_h + R_f + R_v + R_s + \cdots = \sum \text{Sinks} \end{aligned} \tag{7}$$

Then

$$\frac{\mathrm{d}C}{\mathrm{d}t} = -\sum_i \dot{m}_i + \ \mathsf{GPP}\ - \underbrace{(R_a + R_h)}_{\substack{\text{Ecosystem}\\ \text{Respiration}\\ R_e}} - \underbrace{(R_f + R_v + R_s \dots)}_{\substack{\text{Non respiratory}\\ \text{sinks of C}}} \tag{8}$$

In order to correspond to the dominant time scale of observations, the "instantaneous" carbon

[36] A 3D curvilinear box extending above the tallest feature of the ecosystem, and below topsoil, river, lake and stream bottoms, etc.

mass balance equation must be further time-averaged, as denoted by the angular brackets:

$$
\begin{aligned}
\frac{1}{\tau_2-\tau_1}\int_{\tau_1}^{\tau_2}\frac{\mathrm{d}C}{\mathrm{d}t}dt &= -\sum_i \frac{1}{\tau_2-\tau_1}\int_{\tau_1}^{\tau_2}\dot{m}_i(t)dt+ \\
&+\frac{1}{\tau_2-\tau_1}\int_{\tau_1}^{\tau_2}\mathsf{GPP}(t)dt-\frac{1}{\tau_2-\tau_1}\int_{\tau_1}^{\tau_2}R(t)dt \\
\frac{C(\tau_2)-C(\tau_1)}{\tau_2-\tau_1} &= \left\langle\frac{\mathrm{d}C}{\mathrm{d}t}\right\rangle = \underbrace{-\sum_i <\dot{m}_i> + <\mathsf{GPP}> - <R>}_{\substack{\text{Net Ecosystem}\\ \text{Productivity}\\ <\mathsf{NEP}>}}
\end{aligned} \tag{9}
$$

Note that in spirit, the last Eq. (9) is similar to Eqs. (1) and (2) in Randerson et al. (2001), which unfortunately do not distinguish between fluxes and sources and sinks.

> NEP is defined here as the net carbon accumulation by an ecosystem, just as in Randerson et al. (2001). It explicitly incorporates all of the carbon fluxes from an ecosystem, and the interior sources and sinks, including lateral transfers among ecosystems, autotrophic respiration, heterotrophic respiration, losses associated with disturbances, dissolved and particulate carbon losses, carbon burial, and volatile organic compound emissions.

Now, if the time of observation is long enough, the average rate of carbon accumulation in a stable ecosystem should tend to zero because of the Second Law of thermodynamics. Global carbon burial has been about 0.1 percent of terrestrial NPP, see **Figure 15**. Thus, on a time scale of a couple of centuries (Lugo and Brown, 1986; Berner, 2001; Berner, 2003), one may postulate that the rate of carbon accumulation is minuscule compared with the fluxes, sources and sinks, and

> $$< \mathsf{NEP} > \approx 0 \tag{10}$$
>
> Given enough time, stable ecosystems will settle into steady states and recycle almost all carbon (and all other nutrients) in them, see **Table 9**.

Soils, landscapes, and plant communities evolve together through an interdependence on the difference between the rate of soil erosion and soil production (Montgomery, 2007). At steady state this difference must be zero on the average., i.e., the soil erosion rate is equal to the geologic rate of soil production and some equilibrium thickness of soil persists over long time intervals.

Geological erosion rates generally increase from the gently sloping lowland landscapes ($< 10^{-4}$ to 1 mm/yr), to moderate gradient hillslopes of soil-mantled terrain (0.001 to 1 mm/yr), and steep tectonically active alpine landscapes (0.1 to $>$ 10 mm/yr) (cf. Montgomery (2007) and the references therein).

Rates of soil erosion under conventional agricultural practices almost uniformly exceed 0.029 to 0.173 mm/yr (the median and mean geological rate of soil production, respectively), with the data compiled by Montgomery (2007) exhibiting the median and mean values >1 mm/yr. Erosion rates on the steep mountain slopes in Indonesia easily exceed 30 mm/yr (Napitupulu and Ramu, 1982), and the human-disturbed soil can disappear there within days or months, rather than years.

Rates of erosion reported under native vegetation and conventional agriculture show 1.3- to >1000-fold increases, with the median and mean ratios of 18- and 124-fold, respectively for the studies compiled by MONTGOMERY (2007). From my work on the tropical plantations (Patzek and Pimentel, 2006) it follows that the respective ratios are even higher in the mechanically-disturbed hilly landscapes.

For this and many other reasons, humanity's experiment with "Green Revolution" is just a large but temporary disturbance of natural ecosystems driven by a gigantic multi-decade subsidy with old plant carbon (fossil fuels, fertilizers, and field chemicals) into the vastly simplified, fast-eroding, and – therefore – unstable agricultural systems. As such, these latter systems will never test Eq. (10). They will fail much sooner instead.[37]

In addition, a long time-average of the net carbon flow rate out of the system may also be negligible, as most of it is the CO_2 flow rate in for photosynthesis minus the CO_2 flow rate out from respiration. The extreme events[38], such as fires and floods, will be averaged out and in a stable ecosystem soil erosion should also be low (or the ecosystem would not survive, see **Figure 31**). The time-averaged rate of volatile hydrocarbon emissions must be relatively low too, and, therefore, one may postulate that

$$< \mathsf{GPP} > - < R > \approx 0 \tag{11}$$

When averaged over a sufficiently long time, the gross ecosystem productivity is *roughly* equal to the total rate of carbon consumption inside the ecosystem. The origin of this postulate is also the Second Law of thermodynamics.

[37] "One alternative," Prof. HARVEY BLANCH notes, "is to bioengineer a low-lignin crop that does not require fertilizer, that doesn't need much water, and that could be grown on land not suitable for food crops. The problem is that lignin is what makes the plant stalks rigid, and without it, a plant would probably be floppy and difficult to harvest. And of course," he adds, "there might be public resistance to huge plantations of a genetically-modified organism." *Global warming - Building a sustainable biofuel production system*, The News Journal, College of Chemistry, University of California, Berkeley, 14(1), 2006.

[38] *Disturbances* in the ecology parlance.

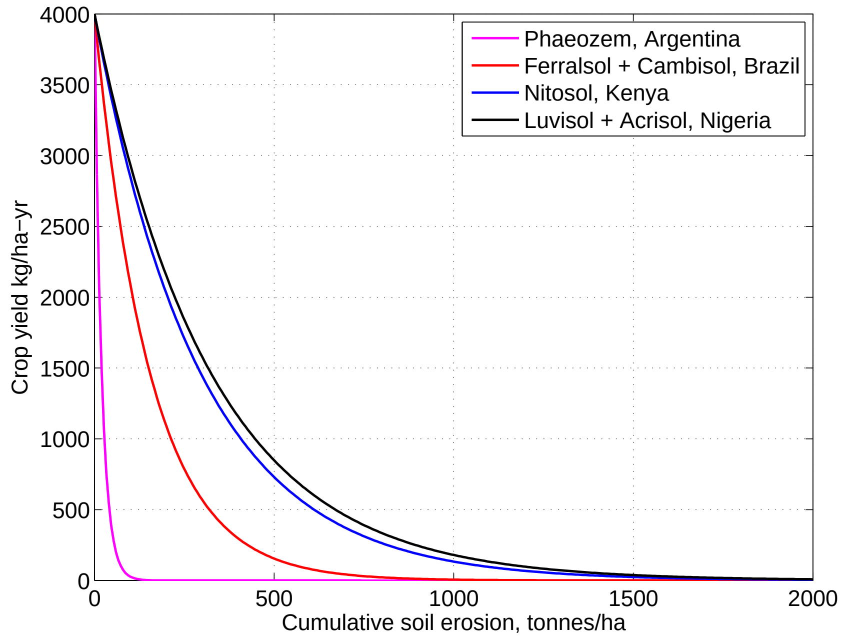

Figure 31: Maize crop yields decay exponentially with eroded soil for a selection of tropical soils: Yield $= 4000\exp[\text{Cumulative Erosion}/r]$, $r = 20 - 300$ t ha^{-1}. The initial yield level is set artificially to 4 tonnes of grain needed by one typical household for 1 year in the subhumid tropics. The cumulative erosion of 10 t ha^{-1} ≈ 1 mm of soil loss. So a loss of 2 cm of topsoil in the tropics is catastrophic. Adapted from Fig. 1 of Stocking (2003).

Table 9: Summary of carbon fluxes in terrestrial ecosystems. Adapted from Tables 1 and 2 in (Randerson et al., 2001) and NASA MODIS data in Table 2

Concept	Acronym symbol	Global flux	Definition
Gross primary production	GPP	110 Gt C/yr	a
Autotrophic respiration	R_a	~1/2 of GPP	b
Net primary production	NPP	~1/2 of GPP	GPP - R_a
Heterotrophic respiration (on land)	R_h	82 - 95% of NPP	c
Ecosystem respiration	R_e	91 - 97% of GPP	$R_a + R_h$
Non-CO_2 losses	$R_v + R_s$	2.8 - 4.9 Gt C/yr	d
Non-respiratory CO_2 losses (fire)	R_f	1.6 - 4.2 Gt C/yr	e
Net ecosystem production	NEP	0 ± 2.0 Gt C/yr	f

[a] Carbon uptake by plants during photosynthesis, see Table 2.
[b] Respiratory (CO_2) loss by plants for construction, maintenance, or ion uptake, see Table 2.
[c] Respiratory (CO2) loss by the heterotrophic community (herbivores, microbes, etc.).
[d] CO, CH_4, isoprene (2-methylbuta-1,3-diene), dissolved inorganic and organic carbon, erosion, etc. These losses are 2.6 to 4.5 % of GPP.
[e] Average combustion flux of CO_2 is 1.5 to 3.8 % of GPP Extreme events, such as the 1997 – 98 El Niño firestorms in Indonesia are excluded.
[f] Total carbon accumulation within the ecosystem: GPP - $R_e - R_f - R_v - R_s - \ldots$. All human crops export about 1.2 to 1.5 Gt C/yr from agricultural ecosystems, while crop residues contain another 1.3 to 1.5 Gt C/yr.

C Environmental Controls on Net Primary Productivity

Net primary productivity is equal to the product of the rate of photosynthesis per unit leaf area and the total surface area of the active leaves per unit area of land, minus the rate of plant respiration per unit area of land. Given sufficient plant nutrients and substrates, temperature and moisture control the rate of photosynthesis.

Extremely cold and hot temperatures limit the rate of photosynthesis. Within the range of temperatures that are tolerated, the rate of photosynthesis generally rises with temperature. Most biological metabolic activity takes place between 0 and 50 ^{0}C. The optimal temperatures for plant productivity coincide with the 15 to 25 ^{0}C optimum temperature range of photosynthesis.

A growing season is the period when temperatures are sufficiently warm to support photosynthesis and a positive net primary production. Warmer temperatures support both higher rates of photosynthesis and a longer growing season, resulting in a higher net primary production – if there are sufficient water and nutrients. The amount of water available to the plant will therefore limit both the rate of photosynthesis and the area of leaves that can be supported.

The influence of temperature and water availability is interrelated. It is the combination of warm temperatures and water supply adequate to meet the demands of transpiration that results in the highest values of primary productivity. Net primary production in ecosystems varies widely, cf. Figure 7 in Cramer et al. (1995) and **Table 10**:

1. The most productive terrestrial ecosystems are tropical evergreen rainforests with high rainfall and warm temperatures. Their net primary productivity ranges from 700 to 1400 g C m^{-2} yr^{-1}.

2. Temperate mixed forests produce between 400 and 1000 g C m^{-2} yr^{-1}.

3. Temperate grassland productivity is between 200 and 500 g C m^{-2} yr^{-1}.

4. Arctic and alpine tundra have productivities of 0 to 300 g C m^{-2} yr^{-1}.

5. Productivity of the open sea is generally low, 10 to 50 g C m^{-2} yr^{-1}.

6. Given equal nutrient supplies, productivity in the open waters of the cool temperate oceans tends to be higher than that of the tropical waters.

7. In areas of upwelling, as near the tropical coast of Peru, productivity can exceed 500 g C m^{-2} yr^{-1}.

8. Coastal ecosystems and continental shelves have higher productivity than open ocean.

9. Swamps and marshes have a net primary production of 1100 g C m^{-2} yr^{-1} or higher.

10. Estuaries and coral reefs have a net primary productivity of 900 g C m^{-2} yr^{-1}. This is caused by the inputs of nutrients from rivers and tides in estuaries, and the changing tides in coral reefs.

High primary productivity results from an energy subsidy to the (generally small) ecosystem. This subsidy results from a warmer temperature, greater rainfall, circulating or moving water that carries in food or additional nutrients. In the case of agriculture, the subsidy comes from fossil fuels for cultivation and irrigation, fertilizers, and the control of pests. Sugarcane has a net productivity of 1700 to 2500 g m^{-2} yr^{-1} of dry stems, and hybrid corn in the US 800 - 1000 g m^{-2} yr^{-1} of dry grain.

Table 10: Average net primary productivity of ecosystems

Ecosystem	Value[a] g C m^{-2} yr^{-1}	Value[b] g m^{-2} yr^{-1}
Swamp and marsh	1130	2500
Algal bed and reef	900	2000
Tropical forest	830	1800
Estuary	810	1800
Temperate forest	560	1250
Boreal forest	360	800
Savanna	320	700
Cultivated land	290	650
Woodland and shrubland	270	600
Grassland	230	500
Lake and stream	230	500
Continental shelf	160	360
Tundra and alpine meadow	65	140
Open ocean	57	125
Desert scrub	32	70
Rock, ice, and sand	15	–

[a] www.vendian.org/envelope/TemporaryURL/draft-npp.html

[b] (Ricklefs, 1990). Note that Column 2 is ~Column 1 × 2.2, corresponding to the mean molecular weight of dry biomass of 26 g/mol per 1 carbon atom, a little less than 27 g/mol in glucose starch, $CH_2O - 1/6H_2O$. A typical molecular composition of dry woody biomass is $CH_{1.4}O_{0.6}$, MW = 23 g/mol.