Green Goo: It's the New Red, White & Blue*
by Robert Kennedy, PE
[written 22Mar09; last updated: 17Sep11]

People look at the corn ethanol situation in the Midwest, and at their own driving habits and conclude, America can never be self-sufficient in biofuel. They say, there simply isn't that much land.
Nothing could be further from the truth. If we never drilled another oil well, or produced another drop of petrochemicals, America could still provide 100% of its liquid-fuel needs from domestic green sources, based on nontraditional crops but traditional American know-how -- if we "merely" had the political will to do so. The total footprint could be as little as 20 million acres, smaller than the State of Tennessee, and less than the fallow land (~36 million acres) that is already set aside under the federal cropland reserve program (CRP) right now. This means no impact on food prices, no displaced cropland, no virgin wilderness turned under the plow, and no morally hazardous food-versus-fuel decisions.

<u>Two Energy Problems, Not One</u>
America (and the world, also) has two energy problems, not one.
Both problems affect national security, energy security, the economy, and the climate, at different temporal and spatial scales.

The first problem is "the Grid", a catch-all term comprising the long-term adequacy and sustainability of electricity generation, transmission, and distribution. The somewhat-greater portion of our long-term energy challenge, as well as its solution, lies in the domain of the Grid.

The second problem is portable liquid fuels for transportation. This other problem is the lesser of the two, barely, but the challenges are more immediate.

The two problems are not very coupled. A simpler way to say this is, turning out the lights will not make gasoline cheaper.

The principal linkage is -- counter intuitively -- water. Generating energy from burning carbon is dependent on water availability, that is, without water for cooling, there is no thermal power; and *vice versa*, for without electricity to run pumps, there is no potable water. Furthermore, because 90% of the impacts of climate change are water-related (too much water where it shouldn't be, not enough where it should be, rapidly changing rainfall patterns in time, and generally more intense and more variable weather), policymakers sometimes speak of the "carbon-water-energy nexus". Also it is said that potable water will become the "oil of the 21st century". However, the carbon-water-energy nexus is another subject for another day.

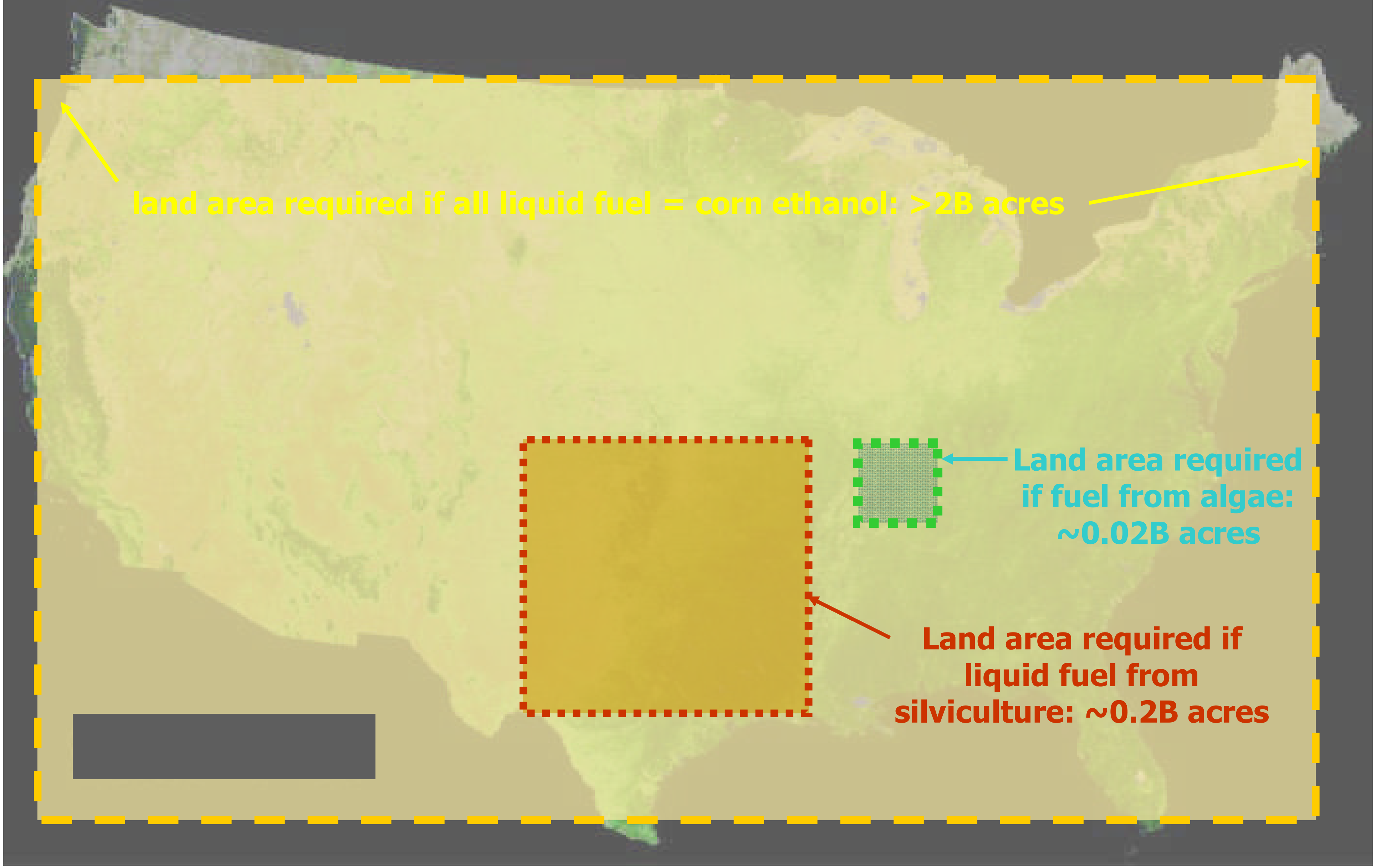
Some promising solutions to the liquid fuel problem, such as plug-in electric hybrid vehicles (PHEVs) will be effective in the short term, but in the long term only shove that problem sideways onto the first problem, the Grid, which is already near its limits now.

The long-term answer is renewable biofuels.

<u>Biofuels for America</u>
Alone among nations, the United States is uniquely situated to completely address its liquid fuel problem via domestic resources. Renewable biofuel provides an ideal historic opportunity to mitigate deep intertwined challenges such as climate change, energy and economic security, and structural under- and unemployment, in a synergistic way.

UNITED STATES

Unique among nations for Biofuels



The USA enjoys:
- lots of cheap arable land;
- lots of sunlight;
- lots of precipitation;
- long growing seasons allowing multiple cropping;
- reasonably decent to excellent soils;
- pre-existing highly mechanized farming;
- a technically-skilled (albeit aging in the ag sector) workforce; and
- extensive road and pipeline distribution networks already in place.

Except for our local soils, which are mediocre, all this is especially true of the Southeast.

<u>What Is Wrong with Making Fuel out of Food</u>
Land Issues: American corn production varies between 120-160 bushels per acre, or 7000-9000 pounds per acre. 1 bushel of dry corn can be converted into 2-½ gallons of ethanol, more or less. Thus an acre of prime cropland can produce 300-400 gallons of ethanol. In total, there are about 2 billion acres in the Lower 48, but that includes deserts, mountains, forests, cities, roads, etc. Only half, about 1 billion acres, is put to use as open rangeland, pasturage, woodland, etc. Only one-sixth, about 340 million acres, is actually “farmed” (by planting and harvesting crops as opposed to ranching or logging), and ~10% of that (36 million acres) is set aside under the federal CRP. Now consider that Americans burn about 200 billion gallons of various petroleum-based fuels in their cars every year, and that ethanol only packs half the punch of gasoline, and that most soils aren't as good as they are in the Midwest (in this case, loess is more). So you can see that the entire land area of the Lower 48 (~2 billion acres) wouldn't be enough to satisfy our needs using fermented corn ethanol.

Energy Efficiency Issues: It takes 2000-4000 gallons of annual rainfall in the Farm Belt to get just 1 gallon of ethanol. Call it 1-to-3000 water efficiency. The energy conversion for sunlight is about as bad as the water conversion. During a year, 60 million Btu of sunlight fall on the ground used to produce that 1 gallon of ethanol. A gallon of corn ethanol has an average heating value of 80,000 Btu. The process efficiency of corn ethanol these days is running about +1.3, i.e. you have to burn one gallon of fuel in order to get 1.3 gallons out, for a net energy benefit of 30%, give or take. At least it's not negative like it used to be, but the net benefit is a mere ~25 thousand Btu per gallon. Sunlight is converted into corn ethanol at only 1-in-2500 exchange ratio.

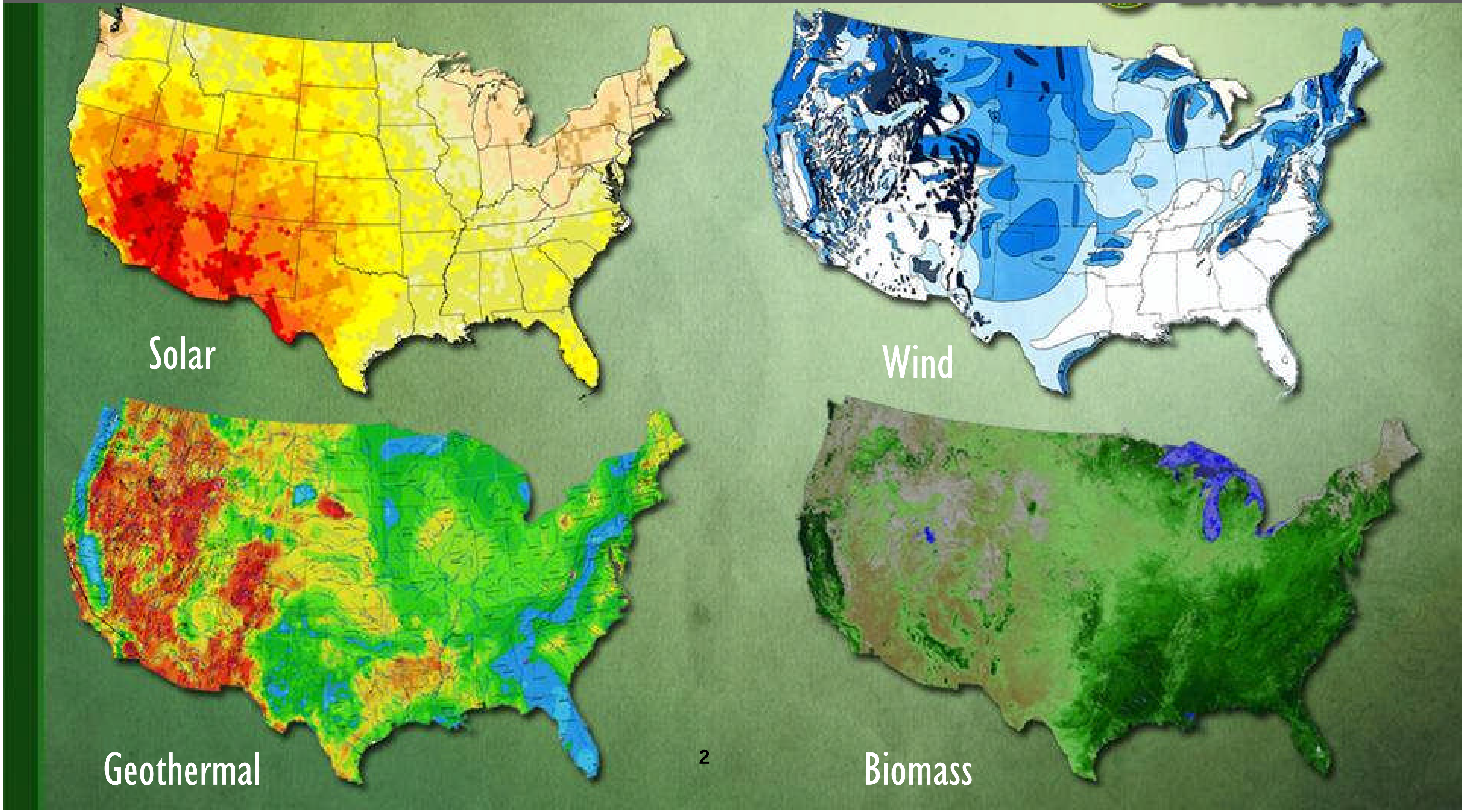
National Security Issues: When you also factor in the national security aspects of price spikes for basic foodstuffs, food shortages, and recent riots over food around the world, corn ethanol does not look like a good deal at all.

<u>Not Corny, but Nuts</u>
The planting and harvesting of non-food energy crops on industrial scales can be a high value-added activity, particularly on marginal lands in the Southeastern quadrant of the country. Because cellulosic ethanol derived from the famous switchgrass still has not been proven at production scale, other "agroenergy" crops are more immediately useful. For example:

- biodiesel from nut trees which promise an order of magnitude more fuel oil per acre than row crops such as soybeans or corn;
- fast-growing tree species such as hybrid poplars and aspen for solid fuel; and
- green waste for polygeneration (an method which delivers more than one form of energy to the end user from the same unit of fuel).

These are examples of "silviculture", i.e. forest agriculture, which in many ways is ideal for the Southeast. Whereas the natural mode of vegetation in the Midwest is grass, the natural mode in the Southeast is forest. For example, if woody/brushy feedstocks for biodiesel (and/or cellulosic ethanol)

RENEWABLE RESOURCES
in the United States are highly regional



were grown along the medians and rights-of-way of the 4 million miles of federal, state, and local highways in this country, enough liquid fuel could be produced to satisfy the nation for about a month. Since the crop is not for human or even animal consumption, a whole bunch of regulatory issues go away. What a perfectly symmetric solution – the farms are obviously road-accessible, and the states already mow those areas anyway! Perhaps some state could pilot a program to produce fuel for state vehicles.

Agroenergy does not have to be restricted to traditional row crops, or brushy weeds, or trees. Algal oil holds even greater promise. The following table illustrates the productive and economic potential of various biofuel crops, in increasing order of yield:

Crop	**Net Yield** [gal/acre/yr]	**Gross Value (range)** [$/acre/yr]
corn oil	19	40 -100
>annual value of carbon sequestration	na	~40
soybean oil	49	100 - 250
mustard seed oil	62	120 - 300
>average product of entire US agricultural sector	na	~300
safflower oil	86	180 - 450
sunflower oil	104	200 - 500
hybrid poplar (cellulosic ethanol)	113	160-280
peanut oil	116	240 - 600
rapeseed (canola) oil	130	250 - 630
neem (tree, value of oilseed only)	130-170	260-870
>average product of US farms only	na	~350
jatropha (nut tree) oil & cellulosic ethanol	174	350 - 880
corn (fermented ethanol)	300 - 400	450 - 1000
coconut (tree) oil	295	600 - 1500
palm oil (nut tree)	650	1300 - 3300
sugar cane or beets (fermented ethanol)	~600-870	900 - 2200
aspen (cellulosic ethanol)		
poplar (cellulosic ethanol)		
cassava (fermented ethanol)		
sorghum (fermented ethanol)	1070	1600-2700
tropical grass/bamboo (cellulosic ethanol)		
miscanthus (cellulosic ethanol)		
switchgrass (cellulosic ethanol)	700-1150	1100-2900
>high-value truck farming, organics, nurseries, etc	na	2000 – 5000+
algal oil w/CO_2 bubbling, lower limit	3600+!	7000 – 18000+

* includes fruits, grains, vegetables, dairy, meat, timber, etc.

Source: Greg Pahl, *Biodiesel: Growing a New Energy Economy* (2005)

As you can see, silviculture (tree-based agriculture) is as productive to twice as productive as traditional row cropping in terms of vegetable oil feedstocks. The great thing about these veggie-like oils is that they can be moved around in regular pipelines and burned in regular engines, which is not true for pure or high-grade ethanol.

The heating value of #1 diesel is ~135,000 Btu per gallon; pure biodiesel is somewhat less, ~120,000 Btu per gallon. The process efficiency of converting veggie oil into biodiesel suitable for engines is very high, i.e. it takes only a small energy fraction for the conversion from a lipid into a fatty-acid-methylated-ester plus some glycerine. It's a simple, low-tech process: add wood alcohol and lye, heat & stir, sit & wait, skim off the supernatant biodiesel, leaving the leftover glycerine for soap or artificial tears. Harvesting nuts from trees might be more difficult than traditional row crops with combines but that's what engineers are for. Let's say the net energy benefit is +100,000 Btu per gallon, which is quadruple corn ethanol's net benefit.

So, since sunlight and rain fall on the land regardless of what's growing on it, the average gross energy efficiency ratio of biodiesel-from-silviculture is ~1:300, and the average net energy efficiency ratio of biodiesel-from-silviculture is ~1:400 -- an order of magnitude better than corn-derived-ethanol! Water conversion efficiency is likewise better.

Thus a horseback analysis suggests that ~200 million acres (that's Texas plus Ohio) under silviculture could provide the equivalent to the USA's entire present annual consumption of petroleum-derived liquid fuels, if all our prime movers were diesels. (But most of our engines are not diesels, and we're ~30% self-sufficient in petroleum right now). This tells me that the USA could be self-sufficient in transportation fuel, if it had the political will to do so. It would require stern conservation, enhanced recovery of traditional and non-traditional petro feedstocks, drastic changes in land use plus impacts on biodiversity, as well as higher prices for everything, but we could technically do it without violating the laws of physics. That's one take-away for you readers. But there's a less painful way.

Making Green from Green Goo

Now consider the last row (algal oil) of the table above, in combination with the amount of farmland idled by federal incentive programs. Algal oils, if we can work out the bugs, would be an order of magnitude more productive than silviculture, and two orders more than present agriculture. Growth can be boosted by keeping the pond water warm with the waste heat from a thermal power plant, and bubbling the CO_2 exhaust through the pond water. Algae can form a wider array of molecular species, hence a number of different fuels. And there's always thermal cracking. Our engines wouldn't have to be all diesels. The process of extracting oil from algae is simple compared to the fermentation and distillation of corn ethanol. Squished algae cakes can be recycled as animal feed. Again, the oily product can be moved around in regular pipelines and burned in regular engines. The main requirements are lots of land for large shallow algal pools, ample fresh make-up water, and stacks of sunlight. Places like Florida would be ideal for open ponds. For places with lots of sun, but little water, or harsh winters, an indoor hydroponic approach with concentrated sunlight would work, at the cost of more capital investment.

So the average gross energy efficiency ratio of biofuel-from-algae is ~1:30!, and the average net energy efficiency ratio of biofuel-from-algae is ~1:40 -- two orders of magnitude better than corn-derived-ethanol! Again, water conversion efficiency is likewise better. 3% efficiency is near the top end of the range of what one can expect for photosynthetic conversion of sunlight into biomass energy on planet Earth.

This back-o'-the-envelope analysis suggests that a mere ~20 million acres under algaculture could provide the USA's entire present annual consumption of liquid fuels, with no restriction on engine type. This is less than the area of the State of Tennessee and a lot less than the 36 million acres already set aside as reserve by federal programs. (Oddly enough, this area is almost equal to the aforementioned medians/rights-of-way surrounding the 4 million miles of highway in this country. 21.3 million acres, to be exact, assuming the average highway is 100 feet wide, including four paved 11-foot lanes, a 6-foot hard shoulder on either side, and .unpaved median/right-of-way.) Which means the land could be repurposed with no effect on existing farmland, food prices, etc. No re-engineering pipelines, infrastructure, and engines! No painful choices! Why aren't we doing this?

Since the median is already a drainage trough by design intent, perhaps medians could be used for the aquaculture portion of the job. One moniker for the venture could be “Carriageway Carbon Corp.” aka CCC. The shoulders could be reserved for silviculture, thus making biodiesel, sequestering carbon, buffering traffic noise, providing habitat for wildlife, and screening the view with pretty trees, all at the same time.

Algae need not be limited to horizontal farming on land. Combined with solar concentrators, algal-fuel could be grown with hydroponic methods in vertical structures. Or algae can be farmed offshore in giant floating non-rigid arrays, illuminated by natural sunlight and pumped through the linear process by natural wave action.

So now you see why the exciting thing is making transportation fuels by farming algae. And we have an existence proof. Algae, after all, is where petroleum comes from in the first place. Does anyone remember "eutrophication" of lakes, the hot-button eco-issue of the early 70s? Same thing.

*kudos to Thomas Friedman

Notes:

* sugarcane yields 65-90 tonnes feedstock/hectare, 700 m^3 water, 1 crop, 300-330 day season, 14% sugar, ~700 gals/acre

* sorghum yields 95-125 tonnes feedstock/hectare, 175 m^3 water, 2 crop (1 main + 1 rattoon), 110-115 day season, 23% sugar, ~1100 gals/acre

* Of the 2 billion acres of land in the Lower 48, ~110 million are “developed” (buildings, roads, parks, but *not* farms). The vast majority of the 110M ac. is paved surface, for motor vehicles. Simply parking Americans’ 250M passenger cars/light trucks takes up 50 billion sq.ft., or 1.1 million acres. When a car moves, it leaves one place and stops at another: since most vehicles are still at any given moment. a minimum of two spaces per vehicle must be allocated, plus maneuvering room to access them, probably equal to another whole space. Say, 3 million acres, just to hold our Detroit iron.