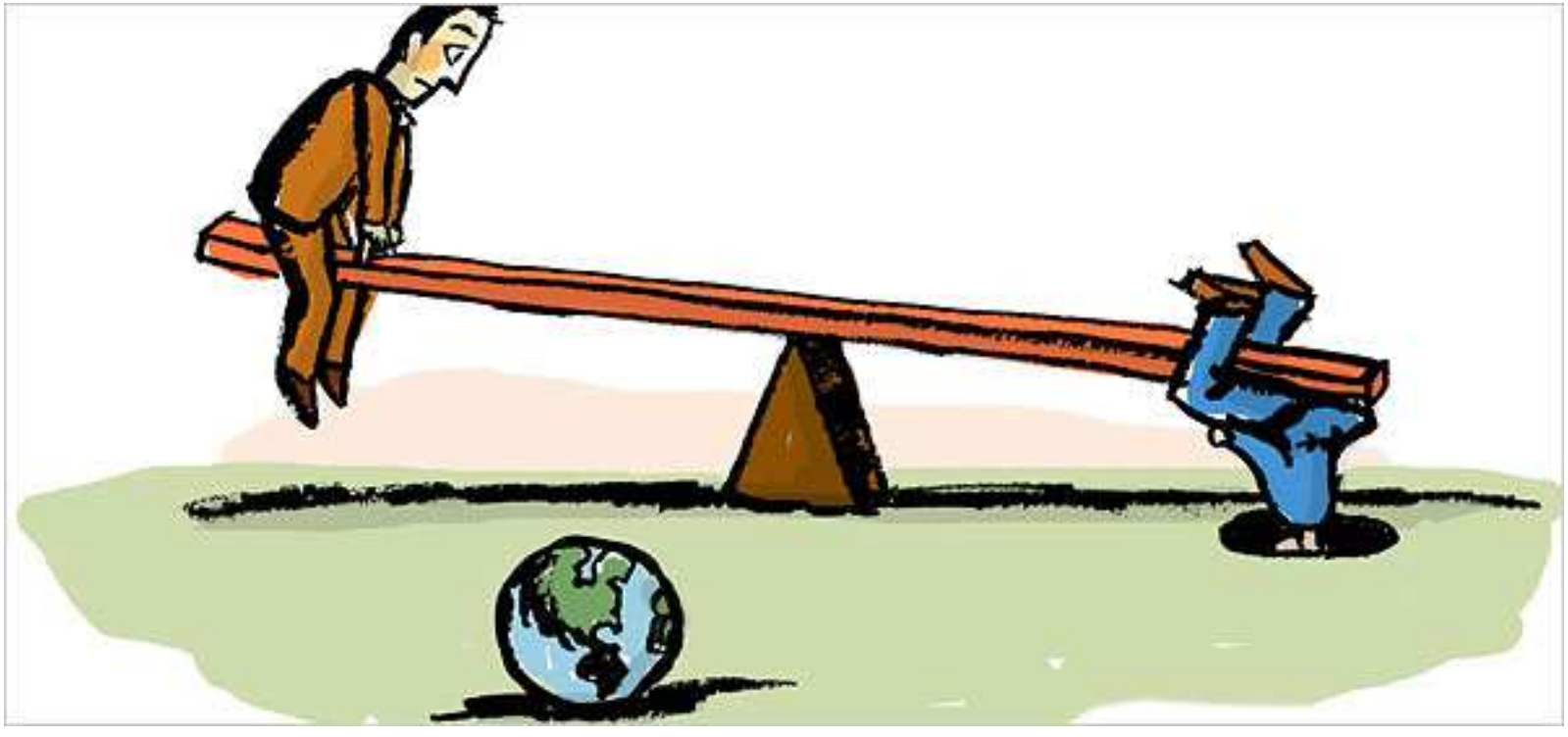
The Biofuel Myths and Facts



ROBERT NEUBECKER, New York Times, 08/15/2006

Tad Patzek, Civil & Environmental Engineering, U.C. Berkeley

September 28, 2006, San Francisco

Motivation

For a successful technology, reality must take precedence over public relations, for Nature cannot be fooled.

RICHARD FEYNMAN, Presidential Commission on the Space Shuttle Challenger Accident, *Appendix F – Personal observations on the reliability of the Shuttle*, June 6, 1986

The Most Important Points

- The astronomic scale of energy consumption from fossil plants and the minute scale of energy production from new plants are fundamentally incompatible
- In engineered crop systems, we continuously apply fossil fuels and nutrients to replenish soil
- What Earth has produced over 400 million years cannot be produced in annual cycles
- If we ever attempt to do so, we will destroy the planet and ourselves
- The initial stage of planetary destruction is well under way
- We must pull back and use fewer resources

Summary of Myths

- US can follow Brazil in replacing 40% of gasoline with ethanol
- US ethanol is plentiful and cheap
- US ethanol production uses little fossil energy
- Ethanol production and use diminish CO_2 emissions
- Fuels from biomass will replace transportation fuels
- In 20-50 years, 50-100 million acres will produce these biomass fuels with future technologies
- Cellulosic ethanol will replace most of US gasoline
- Cellulosic ethanol can be produced efficiently on a large scale
- Biodiesel from soybeans is an efficient biofuel

Summary of Facts

- Brazil replaced 105% of its petroleum use with domestic crude oil production and 8% with ethanol
- US ethanol is limited in supply and very expensive
- 75% of US ethanol energy comes from fossil fuels
- Ethanol production and use increase CO_2 emissions by 50-100% in US, and thousands % in Brazil
- Fuels from biomass cannot replace fossil fuels
- All US land area does not grow enough biomass for our current transportation fuel consumption
- Cellulosic ethanol cannot replace most of gasoline
- Beyond workbench scale, there is no efficient cellulosic ethanol technology

Units in My Presentation...

- The fundamental unit of energy is 1 exa Joule (EJ)

1EJ = 1,000,000,000,000,000,000 J
is the amount of metabolized energy in food sufficient to sustain the entire U.S. population for one year

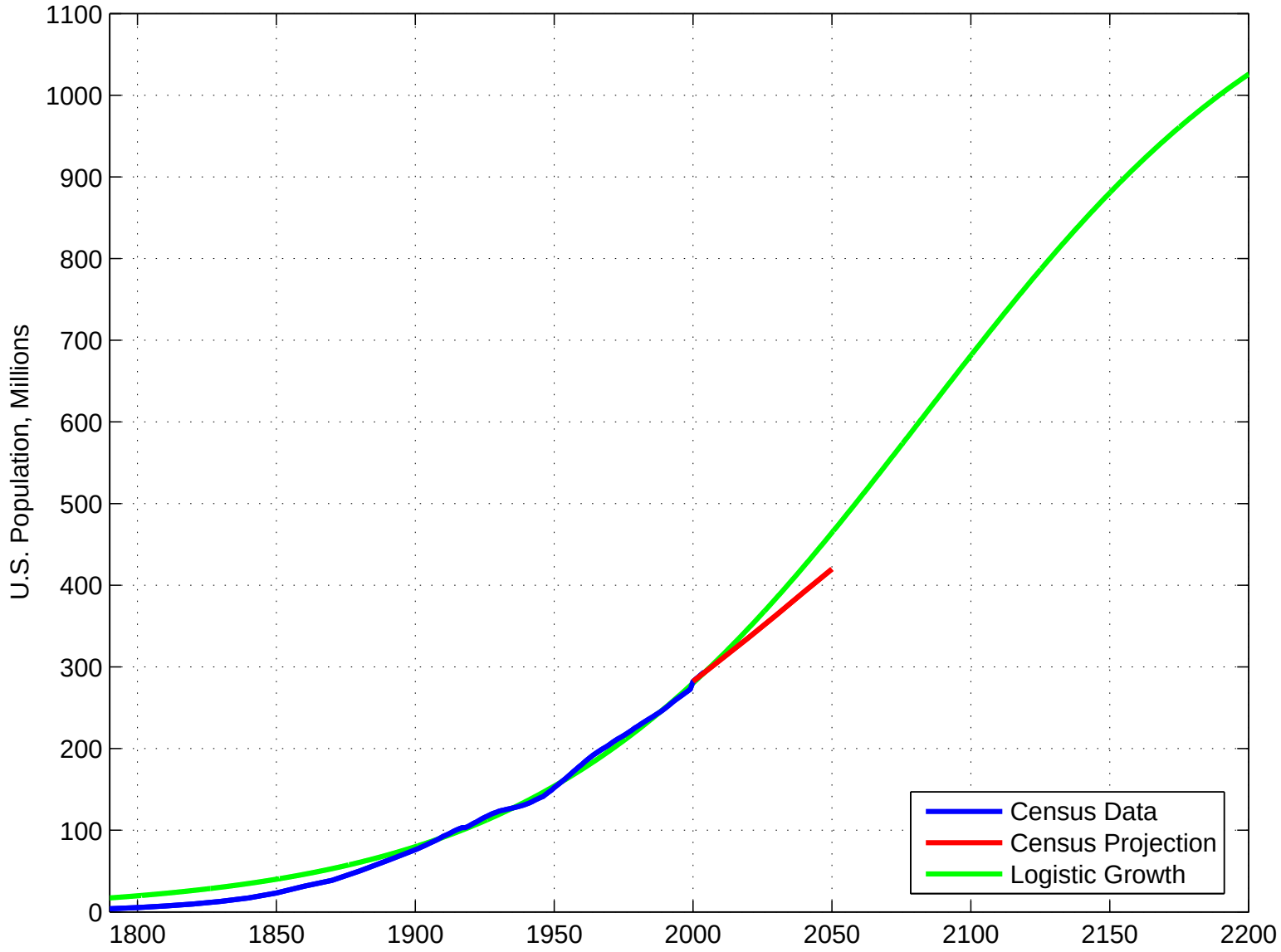
- Currently the U.S. uses 105 EJ/year; one hundred and five times more than we need to live
- If we were to metabolize this amount of energy, we would be 15 m long sperm whales, each weighing 40 tonnes. There are $\sim$1.9 million of sperm whales worldwide and 300 million Americans

Homo Colossus Americanus. . .

1 Statistical American = 1 Sperm Whale

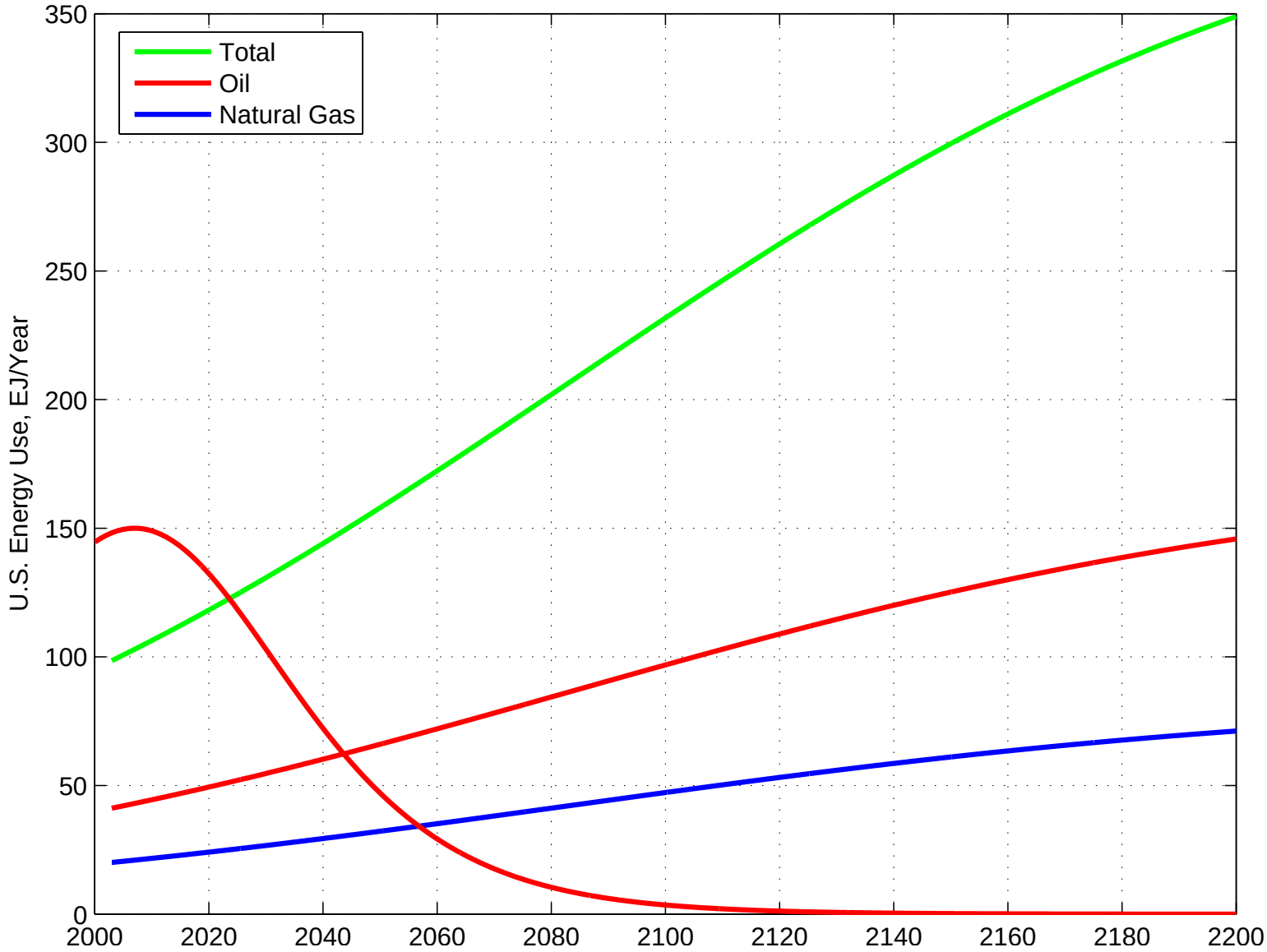
EUGENE ODUM, *Ecological Vignettes*, 1998

US Population Projections



Source: www.census.gov/popest/states/tables/NST-EST2004-01.xls

Projected US Energy Use



Sources: US Census Bureau, EIA, Jean Laherrere, Patzek (2006)

The Problem of Scales. . .

Brief Explanation

Brazilian Ethanol Fuel Claims

"I went down to Brazil and I saw President Lula down there. I don't know if you know this, but the vast majority of fuel to fuel the cars in Brazil is made from sugar."

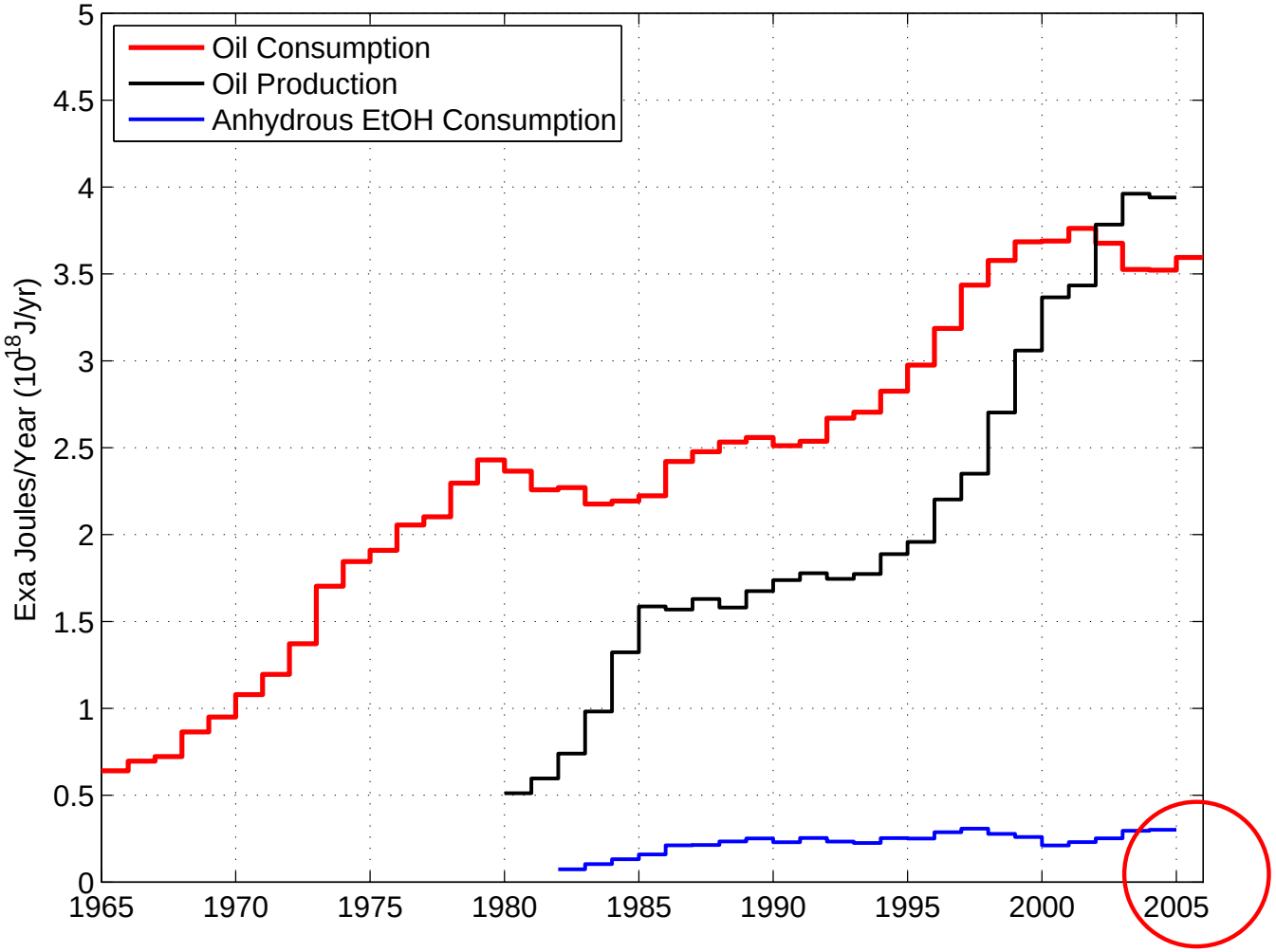
President GEORGE W. BUSH

Advanced Technology Initiative

Feb. 2, 2006, Presentation at 3M in Maplewood, Minn.

Brazilian Energy Supply Claims

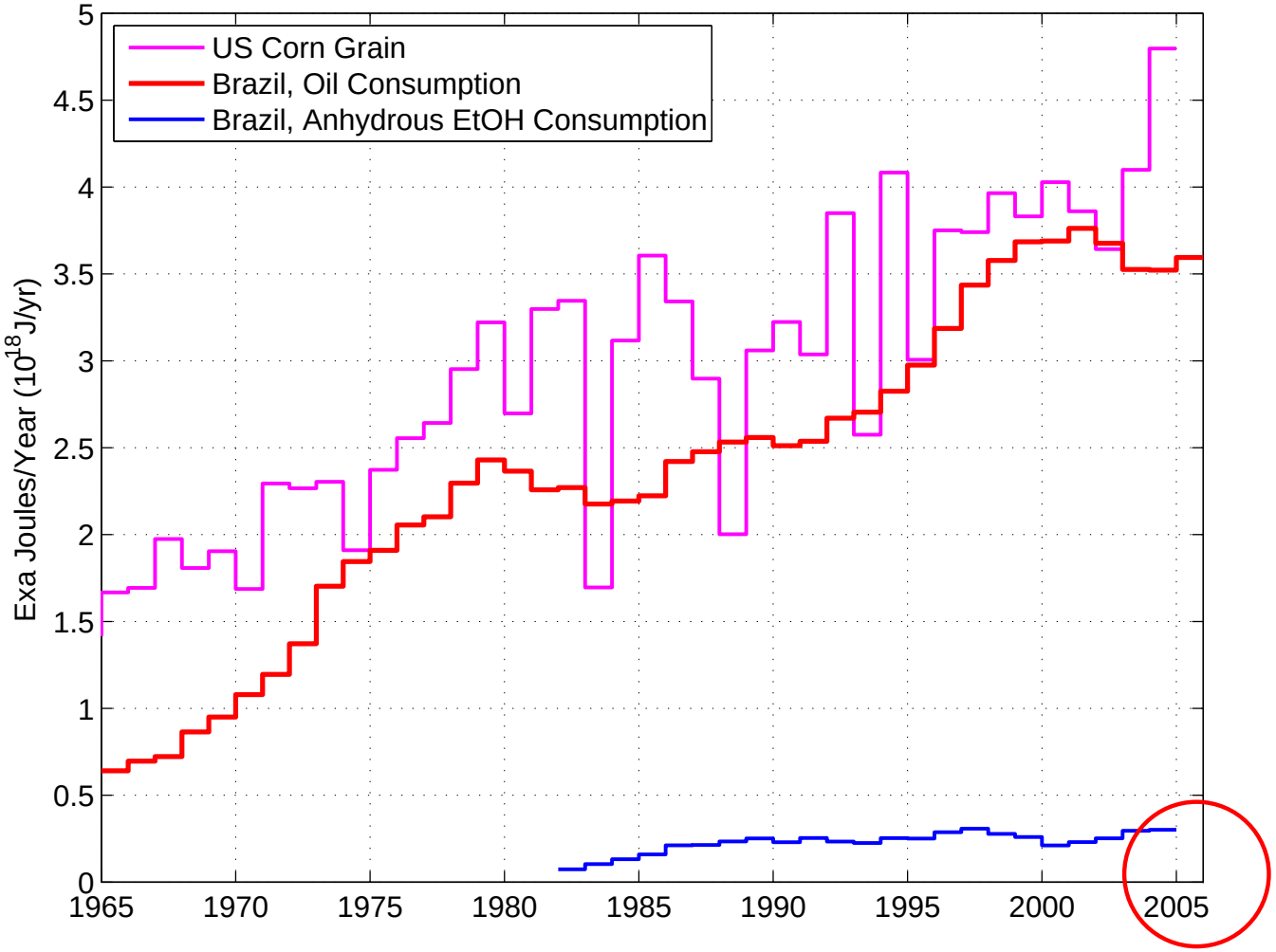
Brazil Replaced 40% of Gasoline Use with Ethanol



Sources: BP, Earth Policy Institute, EIA, Ethanol Producers Association

Do These Claims Make Sense?

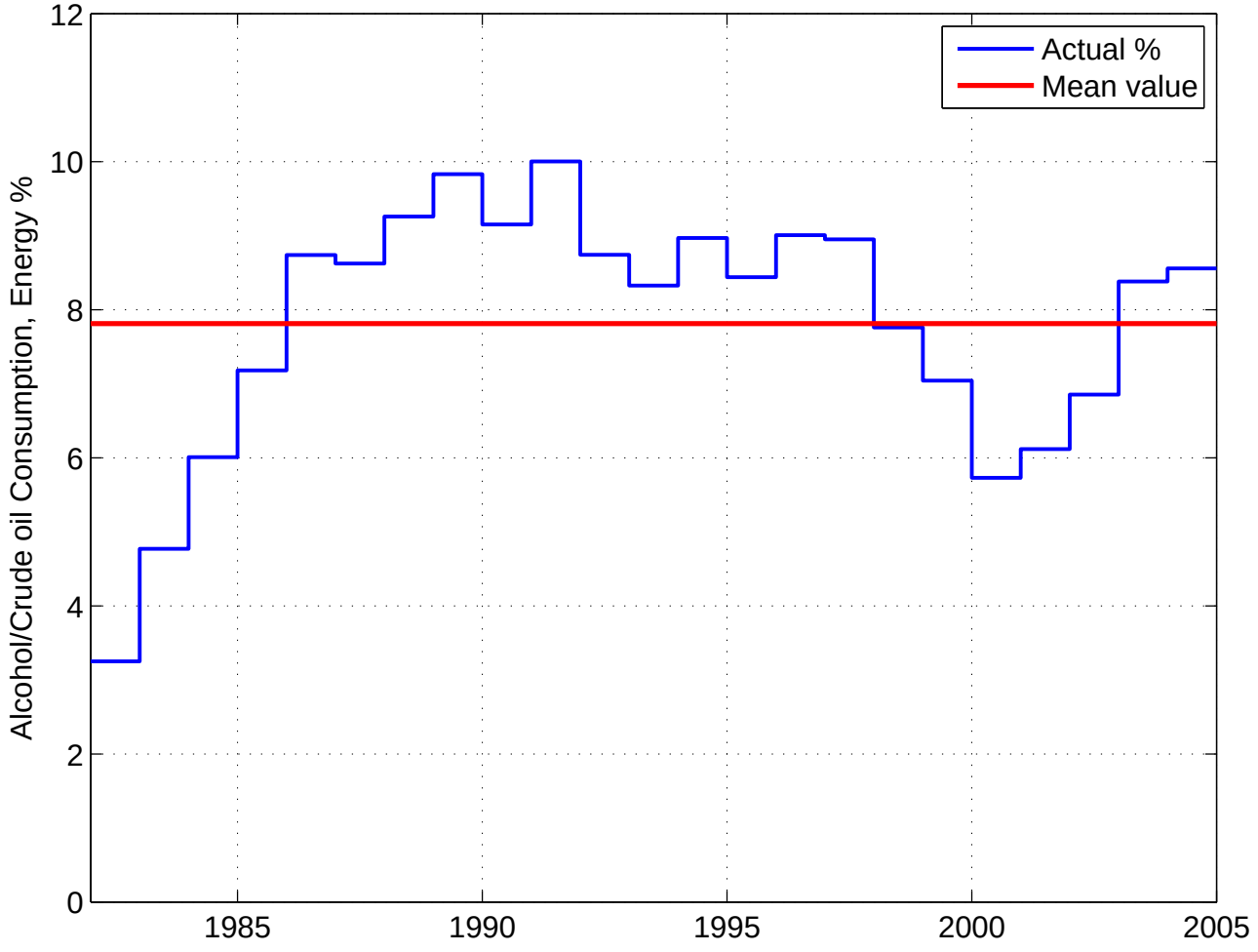
Energy in Brazil's petroleum is less than that in US corn



Sources: BP, Earth Policy Institute, EIA, Ethanol Producers Association

Do These Claims Make Sense?

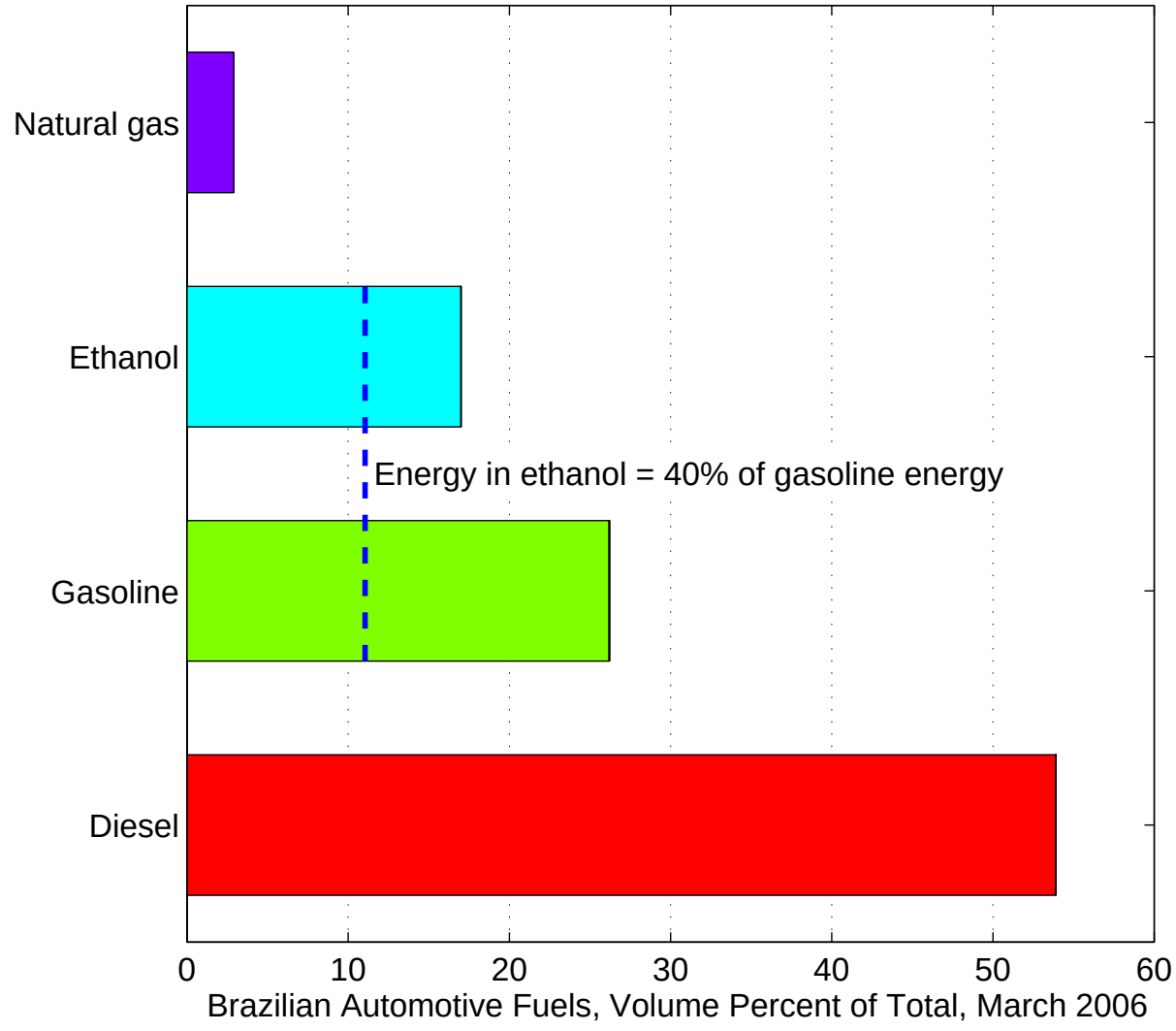
Brazil Replaced 8% of Petroleum with Ethanol



Sources: UNICA, São Paulo Sugarcane Agroindustry Union, Earth Policy Institute

The Reason for the Myth

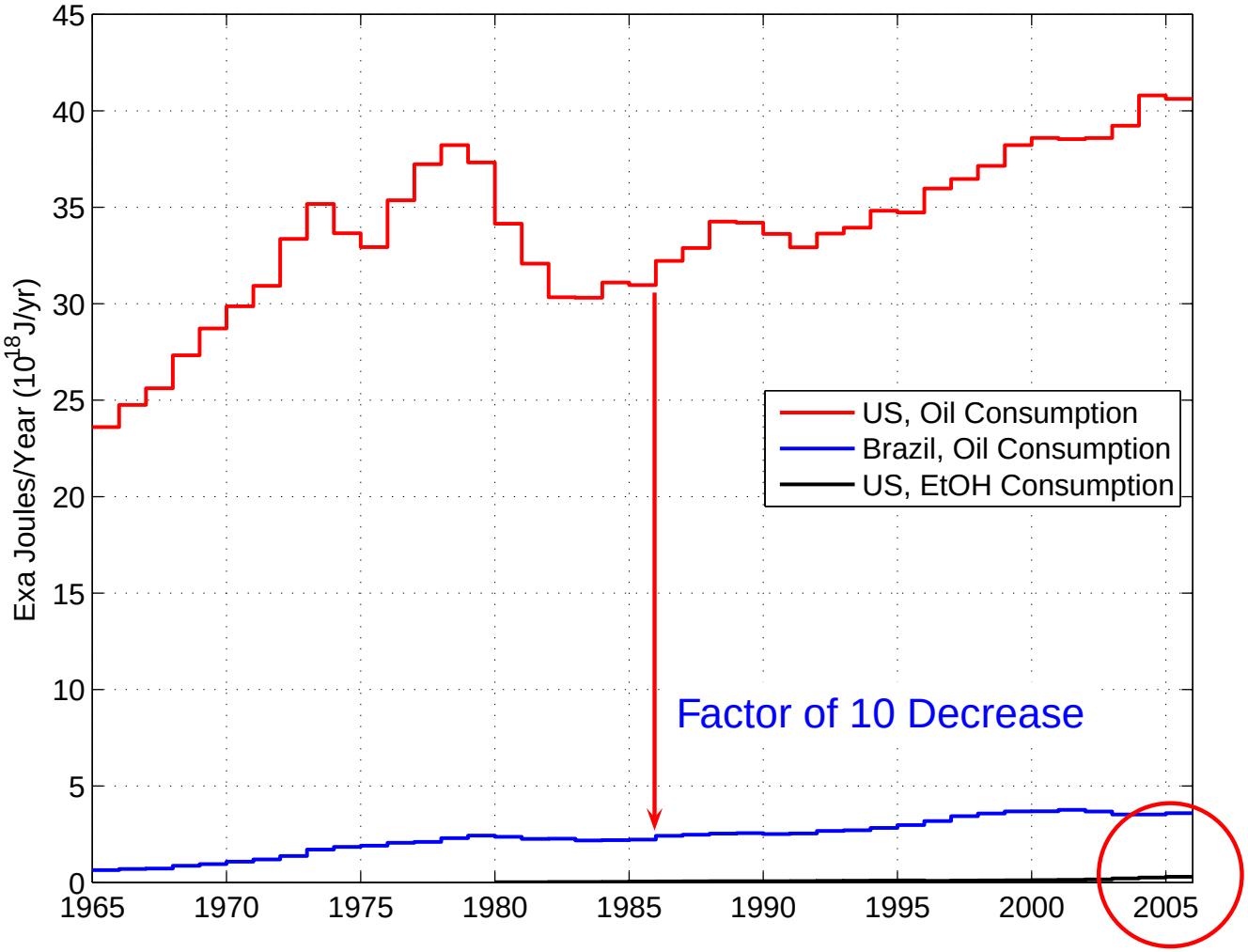
Ethanol Use was 40% of Gasoline Use in Cars



Source: Brazilian Ministry of Mines and Energy

Lessons for the US?

To be a Brazil, Decrease US Petroleum Use 6 times



Sources: BP, EIA, Earth Policy Institute

Facts: US vs Brazil

Unless We Do the Following, Let's Not Deceive US Public:

- For equal per capita use of petroleum, we must cut down petroleum consumption in US by a factor of 6
- This would mean driving all vehicles one day per week
- All passenger cars and SUVs would have to be driven only one day every two weeks

US Ethanol Claims

#1: Ethanol Is Plentiful and Cheap

- “The ethanol is there, the cars are there, we just have no distribution system because the oil companies won’t do it”
- “In the US, ethanol costs about $0.75 – 0.90 a gallon to produce”
- “Compared with any price you can imagine for gasoline, down to about $35 a barrel, ethanol is cheaper”

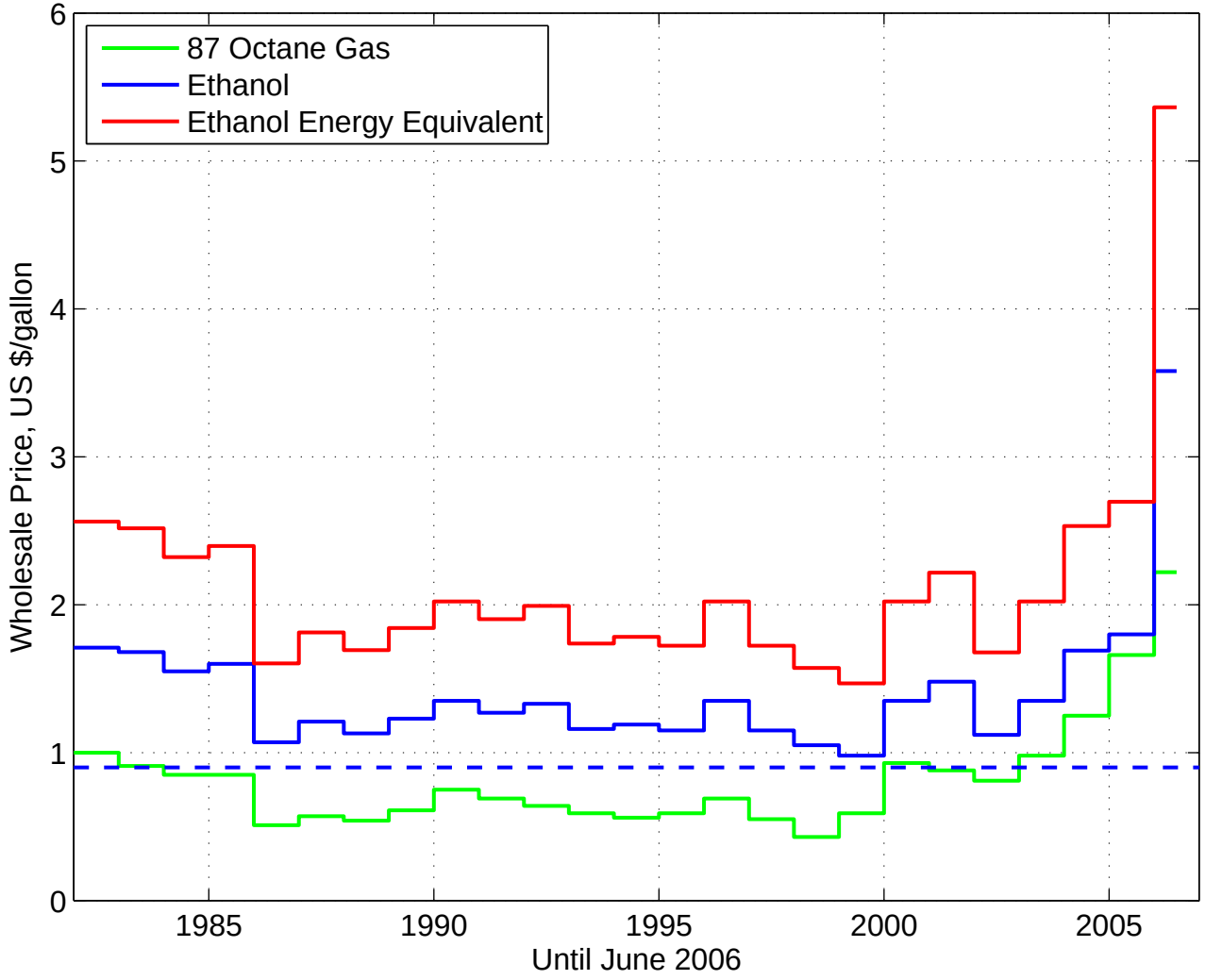
Source: Vinod Khosla, *Biofuels: Think outside the Barrel*, April 2006

True Cost of Ethanol

Fact	Value	Units
Mean ethanol tax credit for “small producers”	0.06	$/gallon
VEETC tax credit	0.51	$/gallon denatured
Mean ethanol tax credits	0.57	$/gallon denatured
Cumulative corn subsidies in US 1995-2004	41.9	$ Billion
Cumulative corn produced in US 1995-2004	95.3	Billion Bushels
Average corn subsidies 1995-2004	0.44	$/bushel
Mean rack price of EtOH (06/19/06)	**3.65**	$/gallon denatured
Mean EtOH yield from 2000 to 2004	2.48	gallons EtOH/bushel
Mean subsidy of EtOH from corn subsidies	0.18	$/gallon EtOH
Mean state subsidies for EtOH	0.15	$/gallon EtOH denatured
Total mean subsidy of EtOH	0.90	$/gallon EtOH denatured
Mean cost of EtOH to taxpayer	**4.55**	**$/gallon EtOH denatured**
Energy equivalent cost of EtOH to taxpayer	**6.91**	**$/gallon GGE**

Do These Claims Make Sense?

US Ethanol is *Very* Expensive, Not Counting the Subsidies



Sources: Sources: Nebraska Ethanol Board; Nebraska Energy Office, Lincoln, NE

US Ethanol Claims

#2: Ethanol Production Uses Little Fossil Energy

- “Corn ethanol has 1.2 to 1.8 of the fossil energy inputs”
- “Petroleum has 0.8 (sic!) of the fossil energy inputs, so ethanol is about twice as good as petroleum”
- “They always forget to mention that petroleum doesn’t produce a unit of energy out for every unit in”
- “There’s petroleum transportation, there’s refining, there’s all those costs”

Source: Vinod Khosla, *Biofuels: Think outside the Barrel*, April 2006

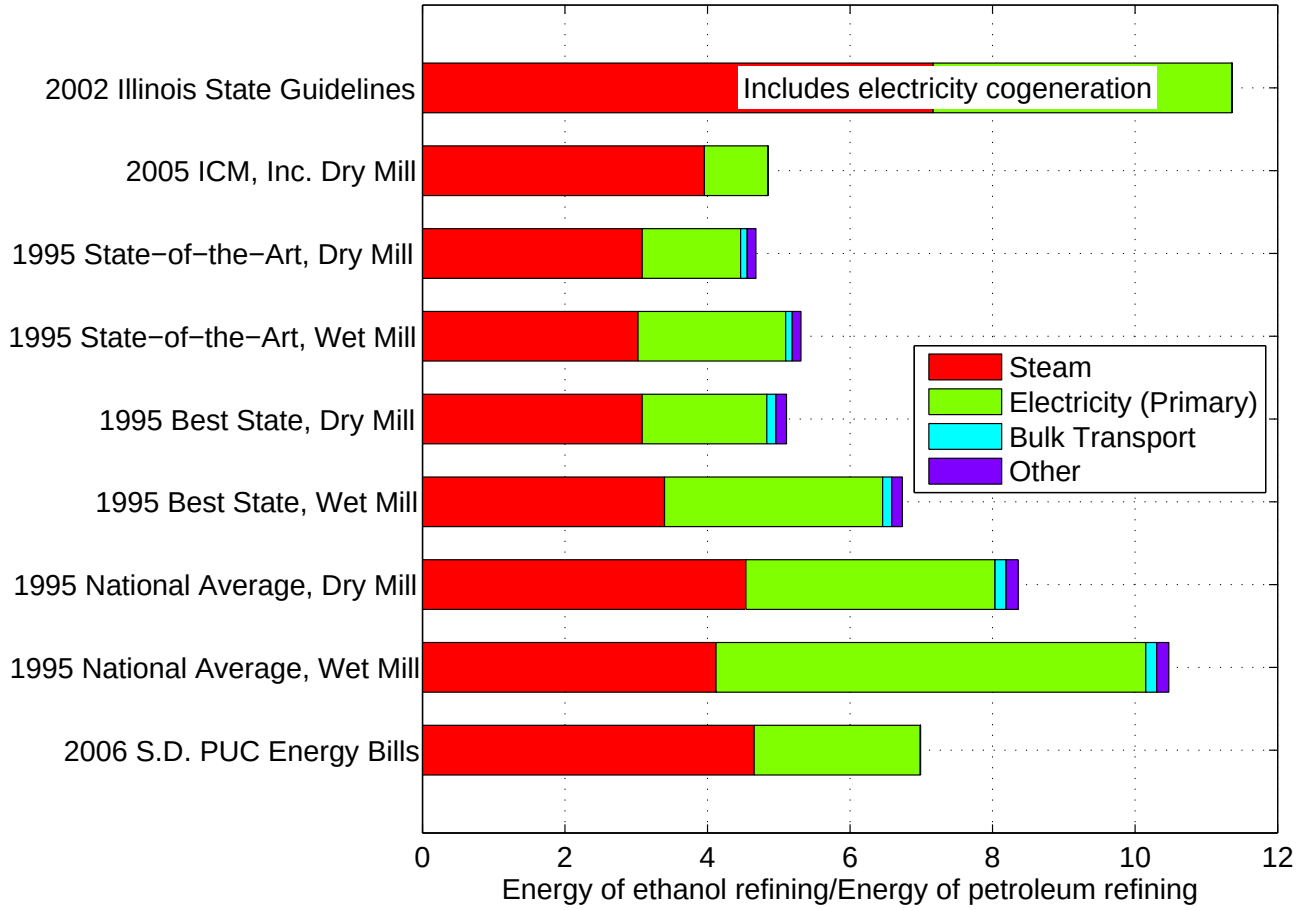
Do These Claims Make Sense?

- Production of gasoline or diesel fuel in your gas station from crude oil at the refinery gate costs *on average* about 11-12% of the chemical energy in this crude oil
- Production of ethanol from corn grain at the plant gate costs at *least* 60% of the chemical energy in this corn grain
- Then you have to truck this ethanol out and distribute it

Sources: DOE NREL (1998), Patzek (2006)

Do These Claims Make Sense?

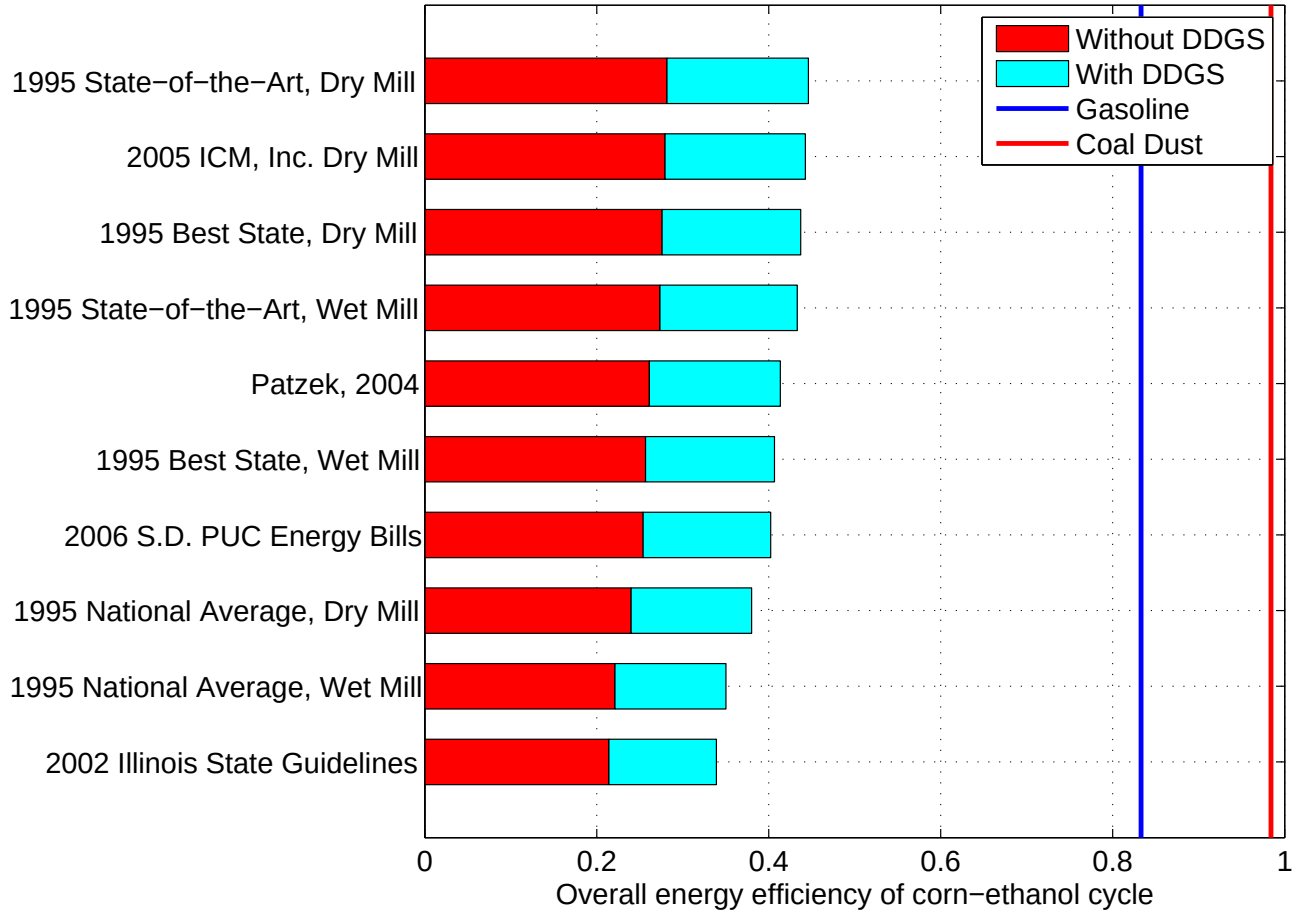
Ethanol Distilleries are $7\times$Less Efficient than Petroleum Refineries



Sources: ICM, MORRIS & AHMED (2000), SHEEHAN ET AL. (1998)

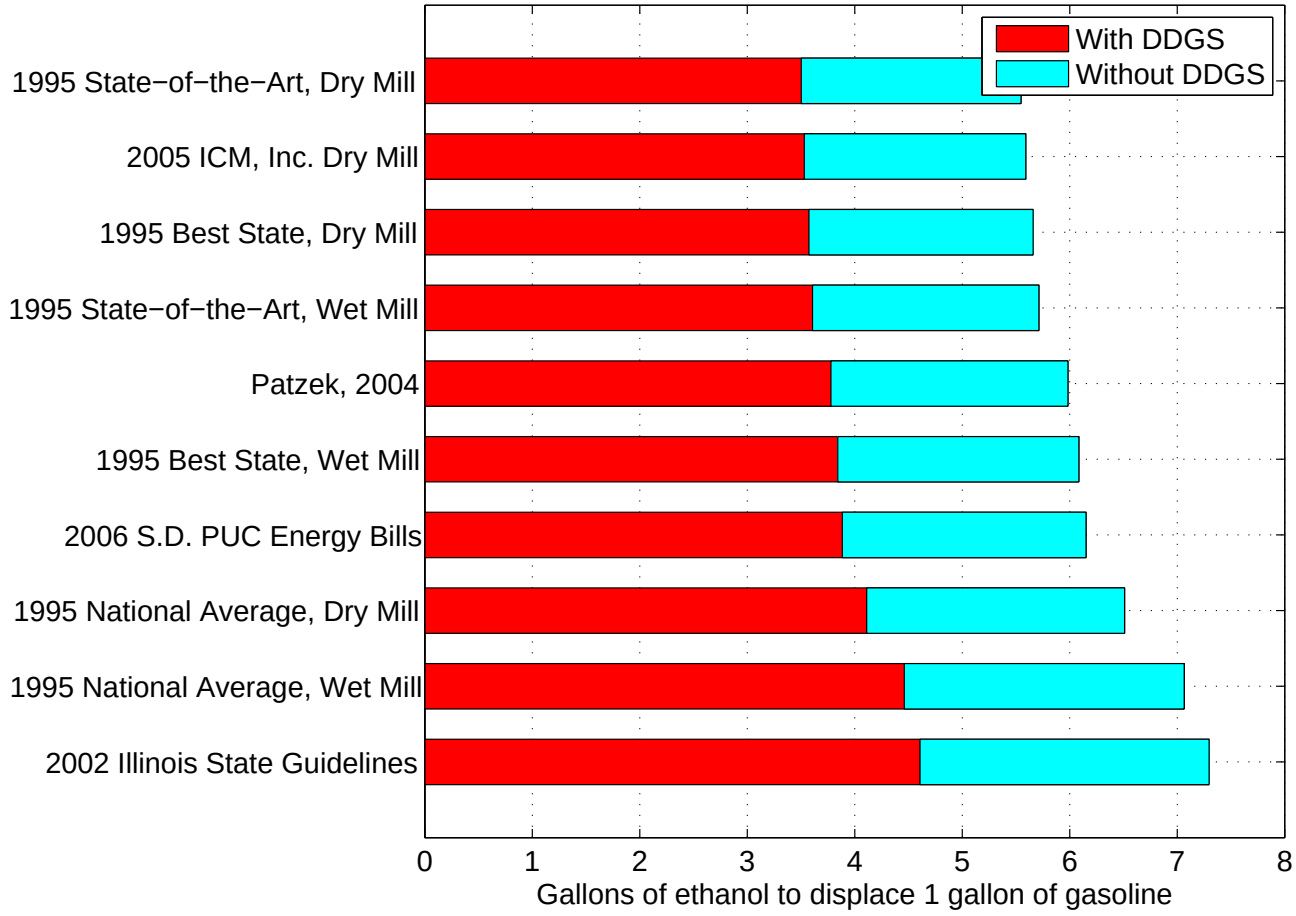
Do These Claims Make Sense?

Ethanol Production is $2-4\times$ Less Efficient than Gasoline



Do These Claims Make Sense?

To displace 1 gallon of gasoline one needs 6.2 gallons of ethanol



Ethanol Claims

#3: Ethanol Production and Use Diminish CO_2 Emissions

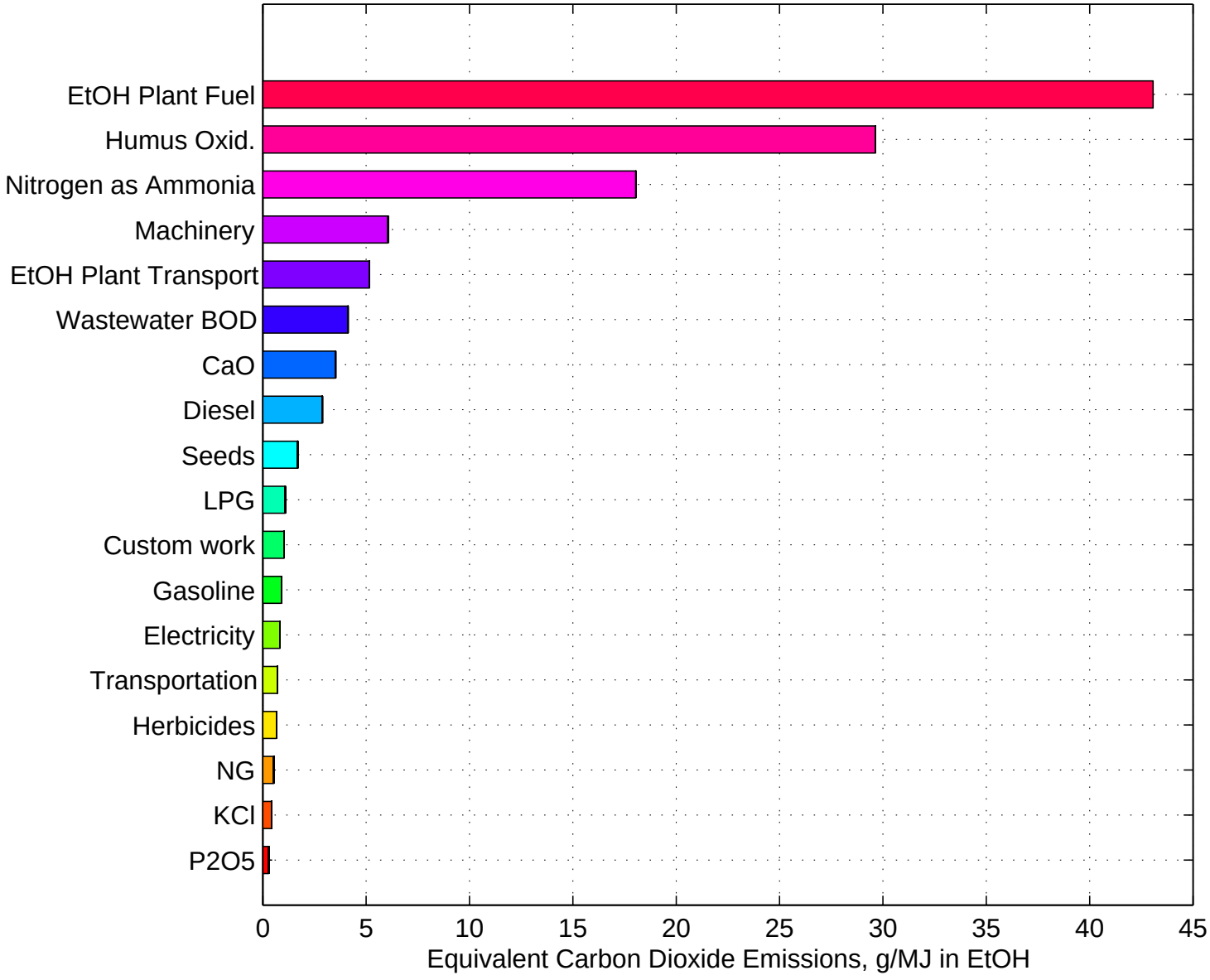
- Corn ethanol provides 20-30% reductions of equivalent CO_2 emissions
- Sugarcane ethanol eliminates almost all emissions of CO_2: “Brazil Ethanol $=\sim$60-80% reduction in GHG”

Source: Vinod Khosla, *Biofuels: Think outside the Barrel*, April 2006

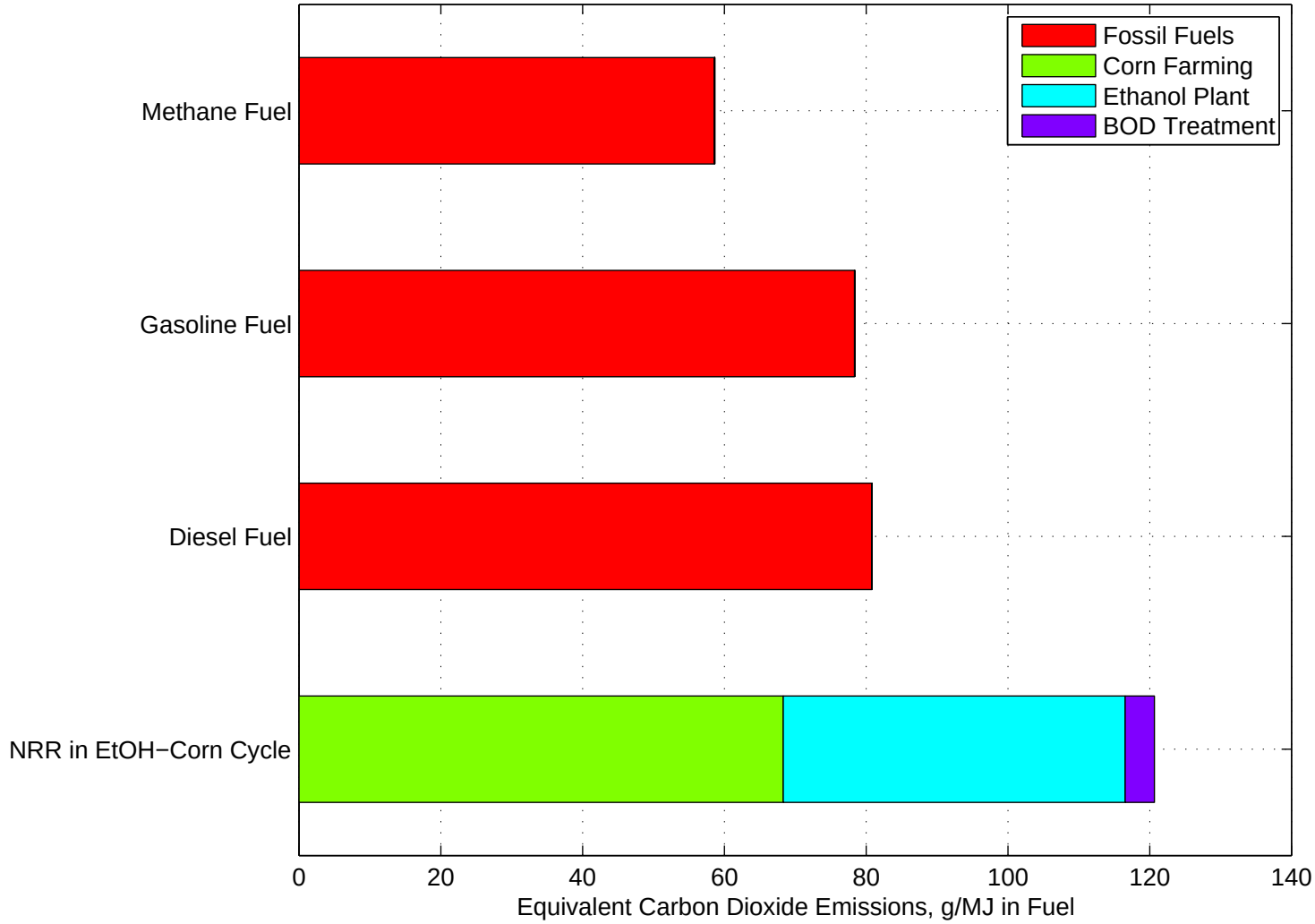
Do These Claims Make Sense?

- Emissions from corn ethanol are $\sim$50% higher than from gasoline or diesel, and 100% higher if one adds cows fed with DDGS
- Sugarcane has caused widespread damage of the Cerrado, high soil erosion, and widespread contamination with field chemicals and vinasse effluent
- Crops displaced by sugarcane from the Cerrado have moved to the Amazon, causing unprecedented deforestation and gigantic CO_2 emissions
- CO_2 emissions from Amazon deforestation and peat oxidation rival the total US CO_2 emissions

CO_2 from NRRs in Corn-EtOH Cycle



CO_2 from NRRs in Corn-EtOH Cycle

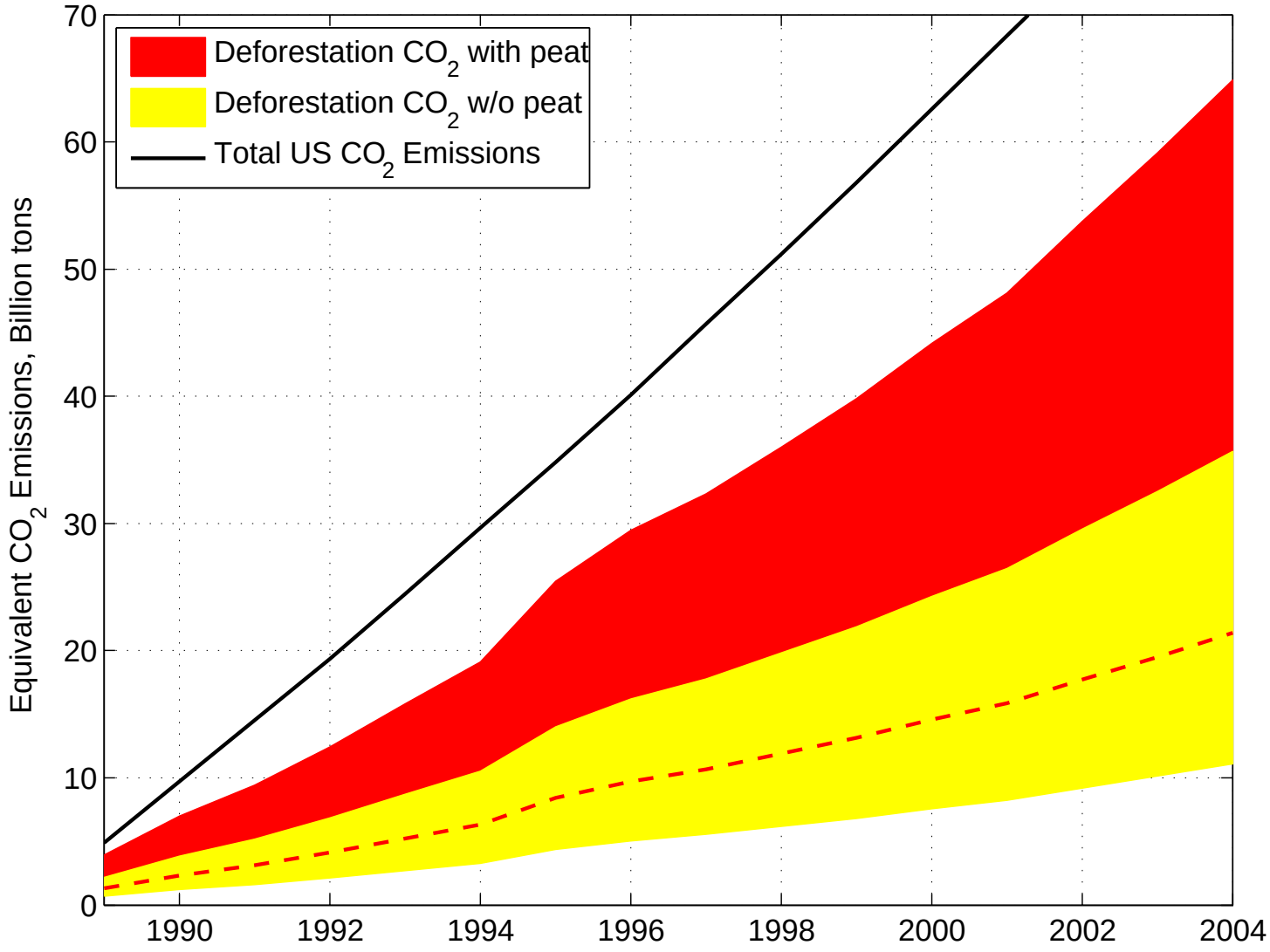


The CO_2 emissions from fossil fuels were increased by 17% to account for their recovery, transport, and refinement activities

Illegal Amazon Deforestation

Source: Greenpeace: 1645 hectares (Gleba do Pacoval area 100 km SE of Santarem) illegally logged to clear land for soya plantations

Cumulative CO_2 from Amazon



Sources: Brazilian National Institute for Space Research (INPE); ORNL; J. Germer and J. Sauerborn, ENVI102, Table 3

Claims of Plentiful Biomass

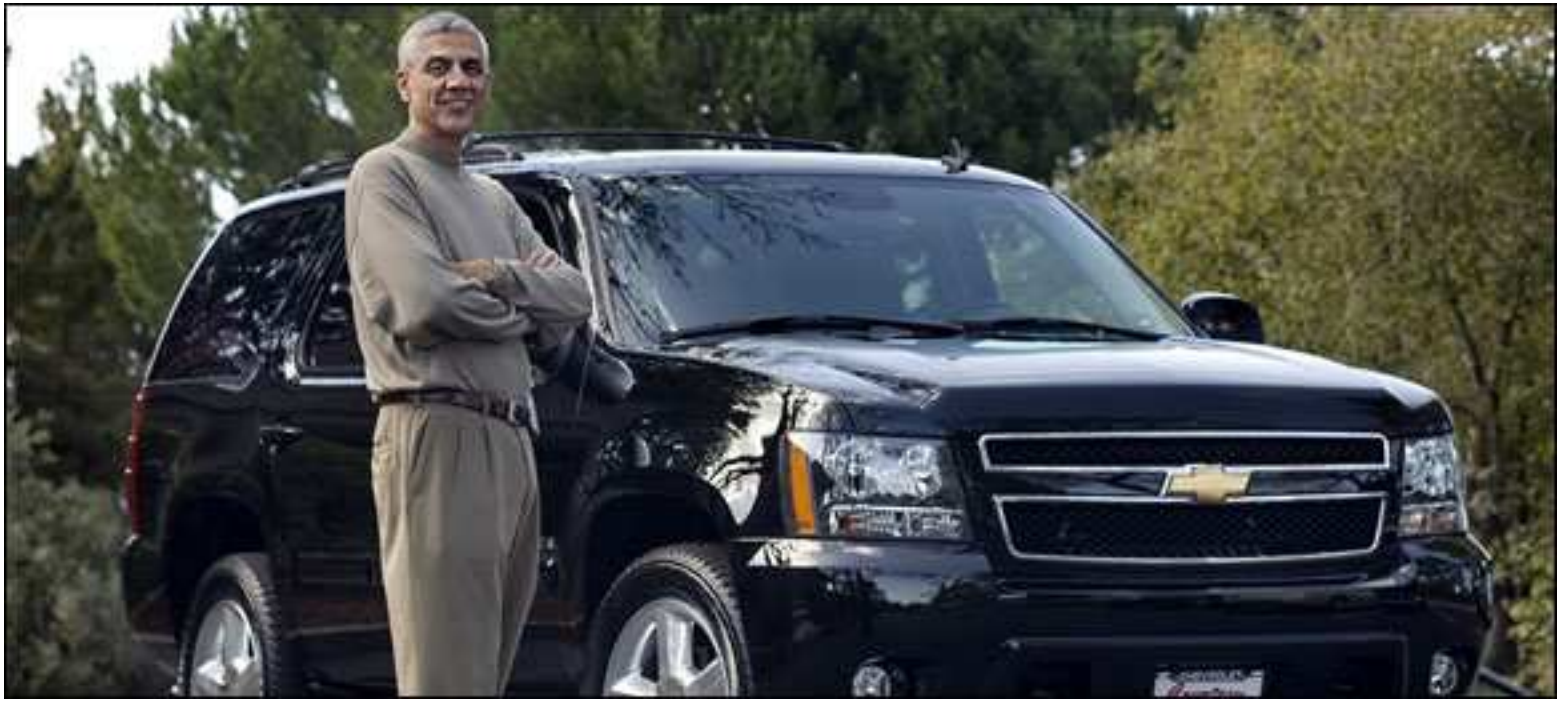
#4: Fuels from Biomass Will Replace Transportation Fuels

- "...An annual biomass supply of more than 1.3 billion dry tons can be accomplished with relatively modest changes in land use and agricultural and forestry practices" *Technical Feasibility of a Billion-Ton Annual Supply US Department of Energy Report*, April 2005
- "Or a 130 billion++ gallons per year!" Vinod Khosla, April 2006 (130 billion gallons of denatured ethanol = 87 billion gallons of gasoline. The US uses 140 billion gallons of gasoline per year)
- "Our goal is replacing 30% of transportation fuels with biofuels by 2030," DOE Secretary Bodman

Do These Claims Make Sense?

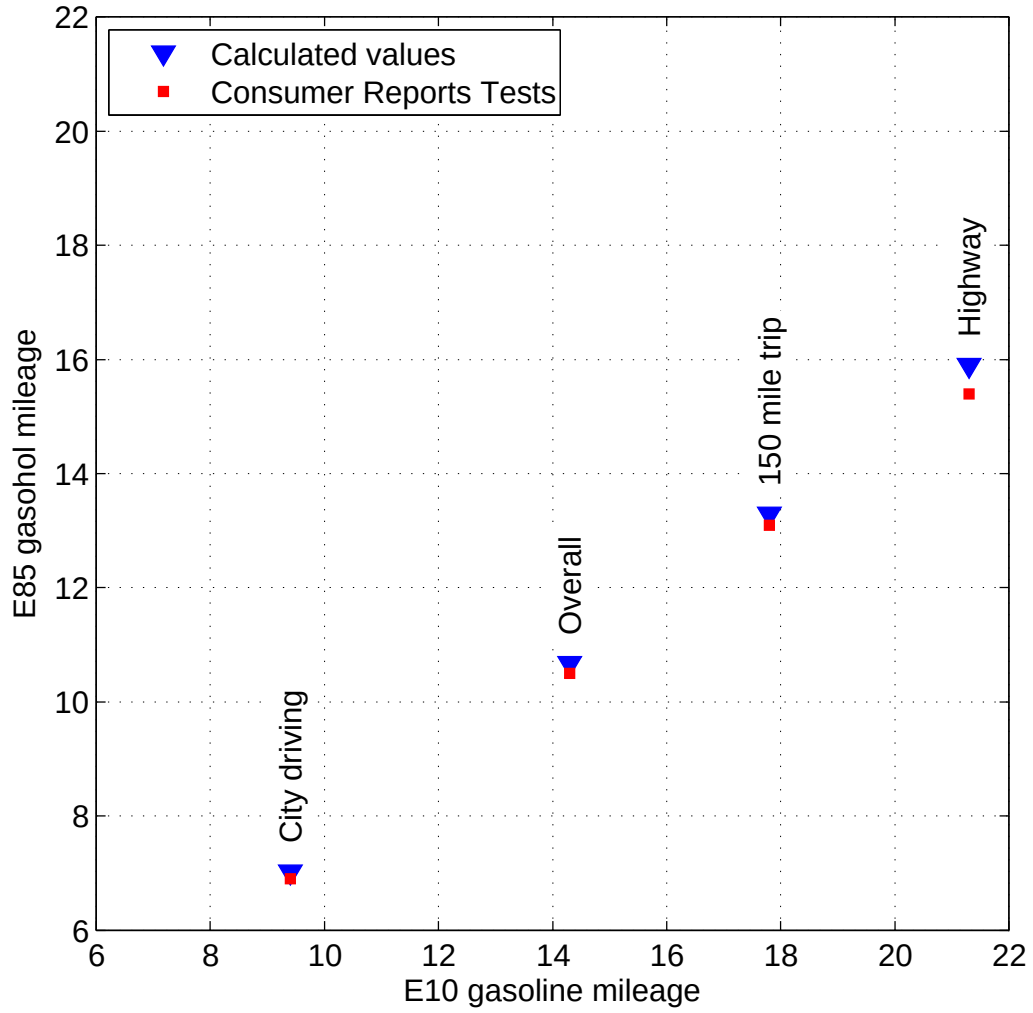
- 130 billion gallons of ethanol is 11.4 EJ per year
- 1.3 billion tons of dry mass is 22 EJ per year, year-after-year, for decades
- Overall conversion efficiency, $11.4/22 = 0.52$ is over 2 times higher than the average energy efficiency of the corn-ethanol cycle
- Current corn production is from best agricultural land in the US, and this efficiency can only go down, not up
- Industrial cellulosic ethanol technology does not exist
- Biomass gasification is in an early pilot stage

FFV Chevy Tahoe Tested by CR



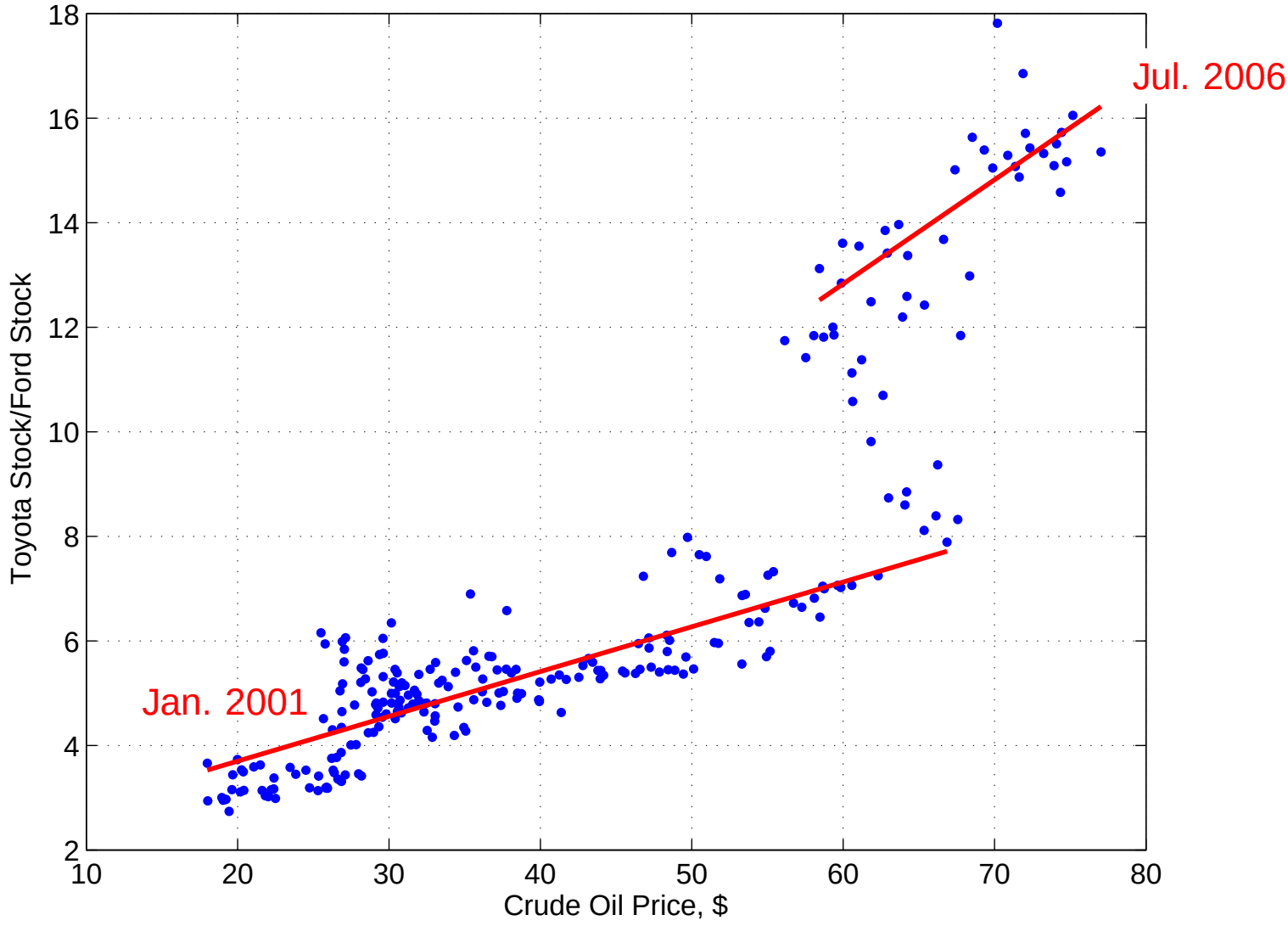
Source: NORM ALSTER *On the Ethanol Bandwagon, Big Names and Big Risks*, NYT, March 26, 2006

Mileage = Fuel Energy



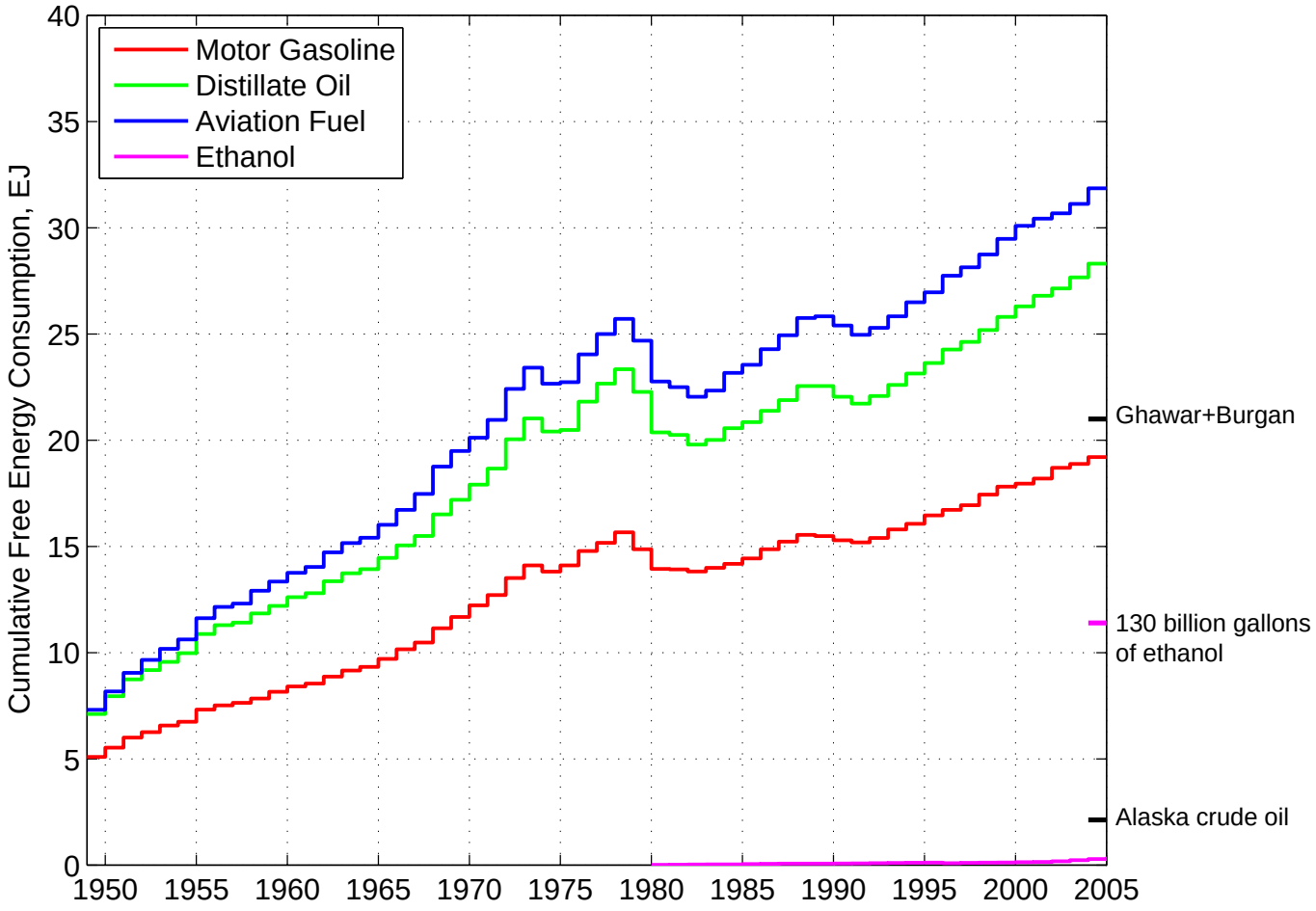
Under the CAFE formula a 2007 Tahoe truck would receive a CAFE rating of 21 mpg, but a 2007 Tahoe truck with an FFV engine would be rated at 35 mpg. Sources: Consumer Reports, Oct 2006; Patzek (2006)

American Consumers Do Understand



Source: STEPHEN SCHORK, The Schork Report, www.EnergyMarketIntelligence.com

Transportation Fuels in US



Sources: US DOE EIA, Patzek (2004)

Ghawar and Burgan are two most productive oilfields on the earth

US Biomass Facts. . .

Brief Explanation

All flesh is *plants* $\sim$ *Isaiah*

Three hundred trout are needed to support one man for a year. The trout, in turn, must consume 90,000 frogs, that must consume 27 million grasshoppers that live off of 1 million kilograms of grass.

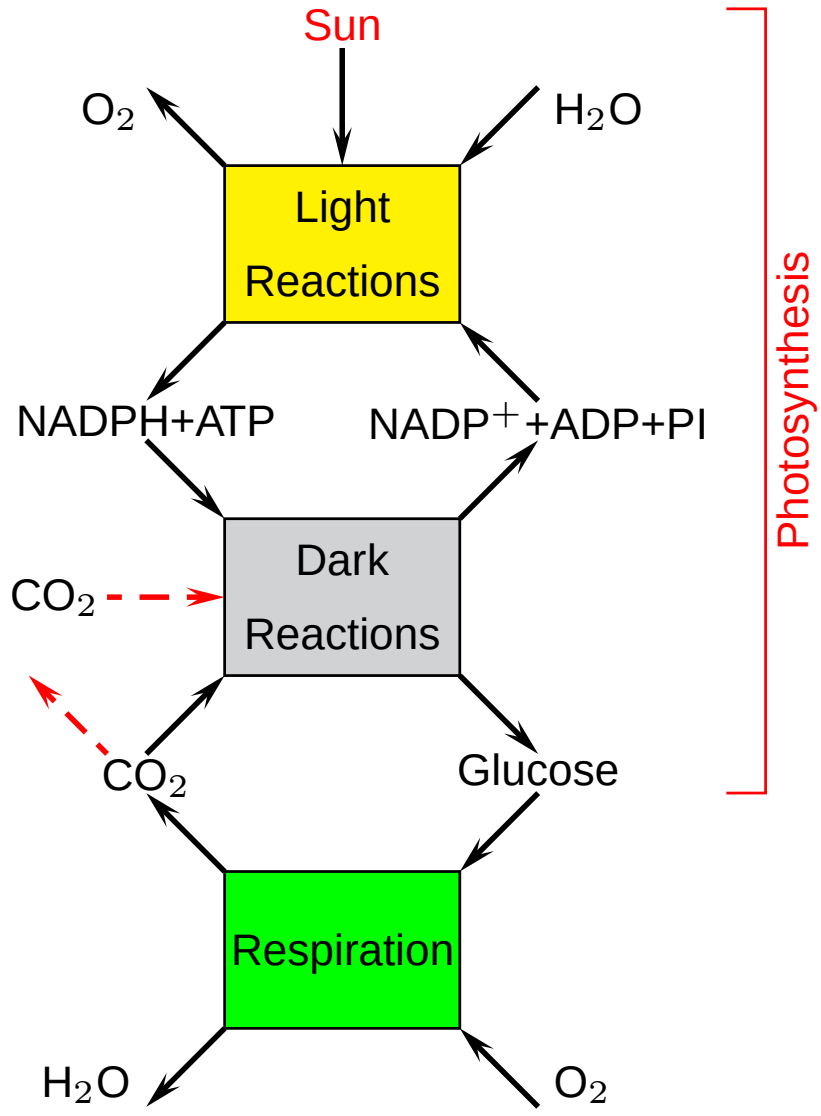
G. TYLER MILLER, JR., *Energetics, Kinetics and Life*, Belmont, California, Wadsworth, 1971, p. 46

Photosynthesis. . .

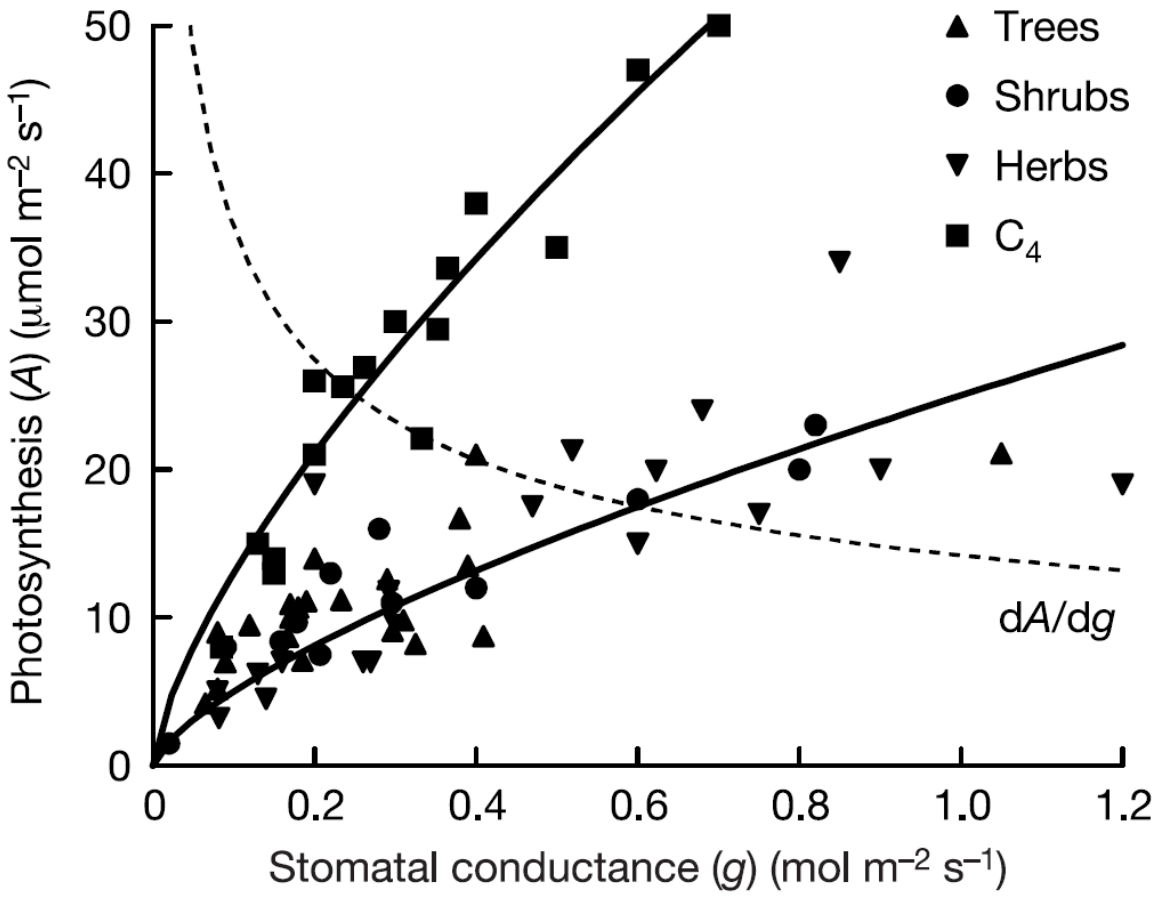
Ecosystem Productivity:

- Gross Primary Production (*GPP*) = CO_2 fixed by plants as glucose
- Respiration (*R*)=CO_2 released by metabolic activity of plants R_p, animals R_h, and decomposers R_d
- Net Primary Production, *NPP*
  $NPP = GPP - R_p$
- Net Ecosystem Production

  $NEP = NPP - \mathbf{R_h} - R_d$
- In natural ecosystems, $NEP \approx 0$
- Humans command $\sim$40 % of global NPP, but return next to nothing



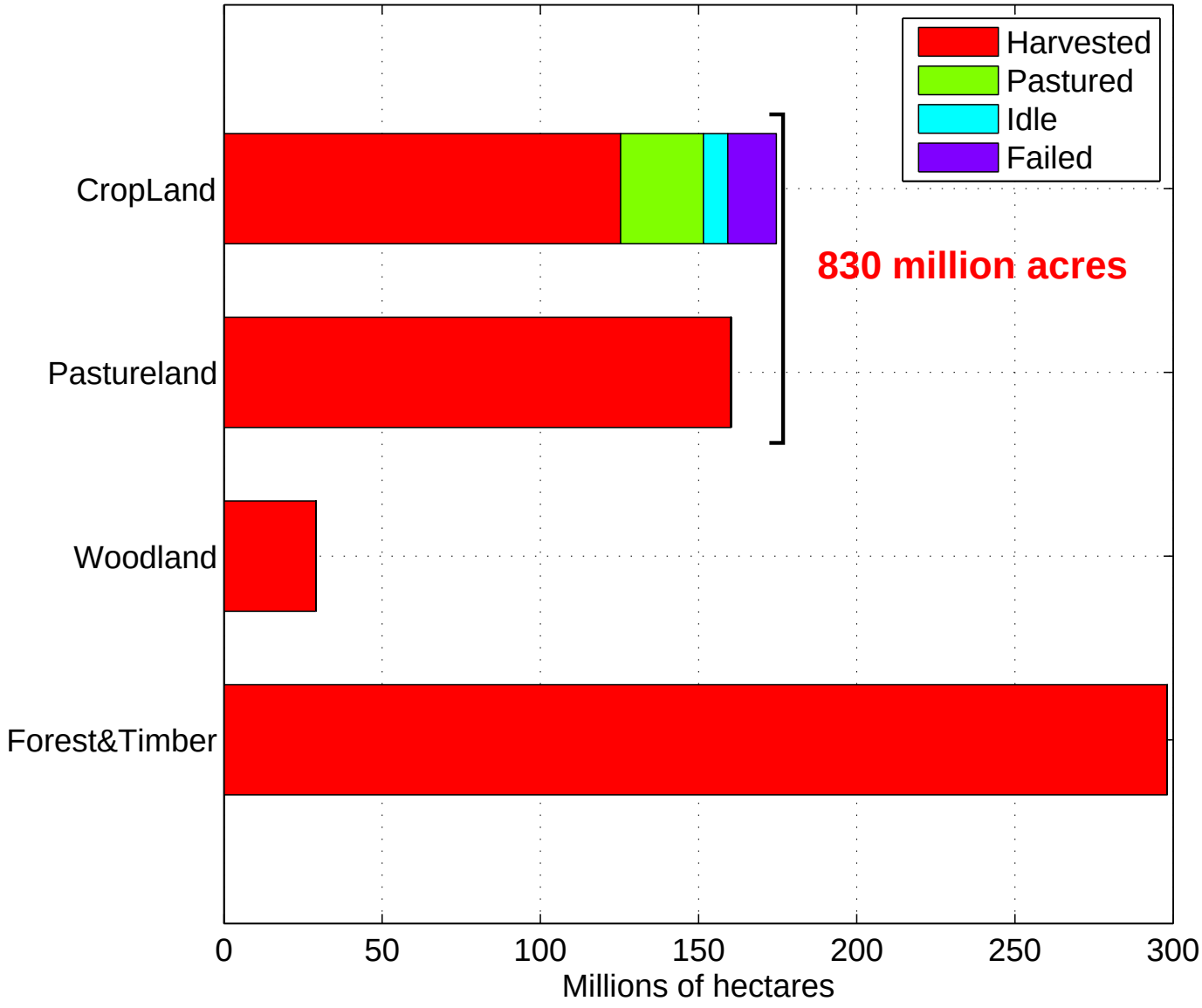
Photosynthesis Uses Water



Rule of thumb: 200-1000 kg of water is transpired by leaves for 1 kg of fixed CO_2

Source: A. M. HETHERINGTON & F. I. WOODWARD, *The role of stomata in sensing and driving environmental change*, Nature, **424**, 901 - 908

Green Land Area in US



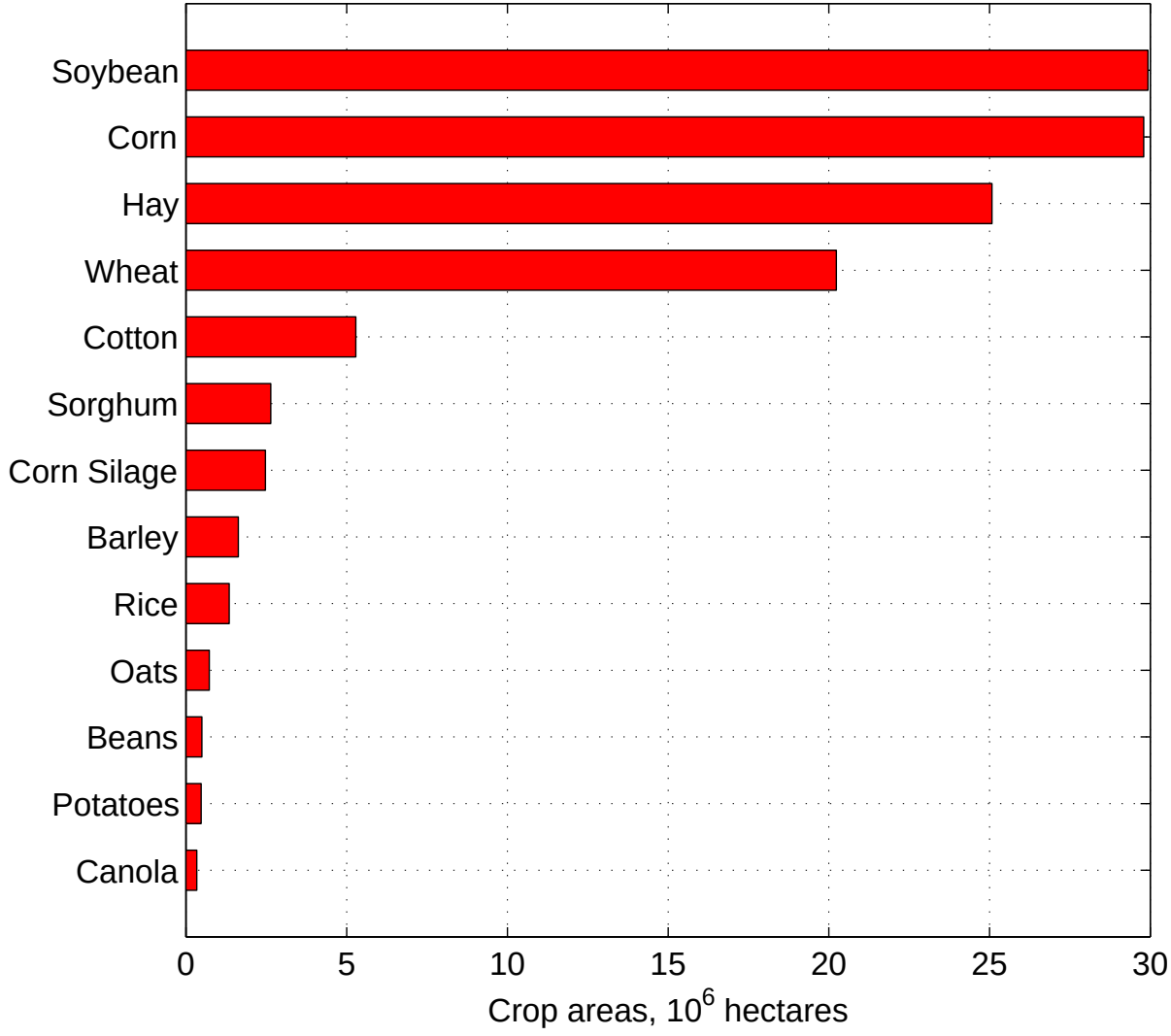
72% of land area in US+Alaska+Hawaii. Sources: USDA, US Forest Service

US Land Consumption

- 3,000 acres of farm land are lost every day for "development"
- Often the best farmland goes first
- And the rate of loss is accelerating - 1.2 million acres were lost annually from 1992-1997, a rate over 50% higher than 1982-1992
- At current rate, 30 million acres of prime farmland will disappear by 2030
- Therefore, the per capita acres of farmland will decrease from 1.3 acres in 2006 to 0.8-0.7 acres in 2050, depending on the population growth

Sources: *U.S. National Report on Population and the Environment*, Center for Environment and Population, 2006, and references therein

US Agriculture: Crop Areas



Source: USDA NASS, 2004. Total crop area 120 Mha (300 million acres)

Crop→Plant Biomass Conversion

One needs

- Harvest index

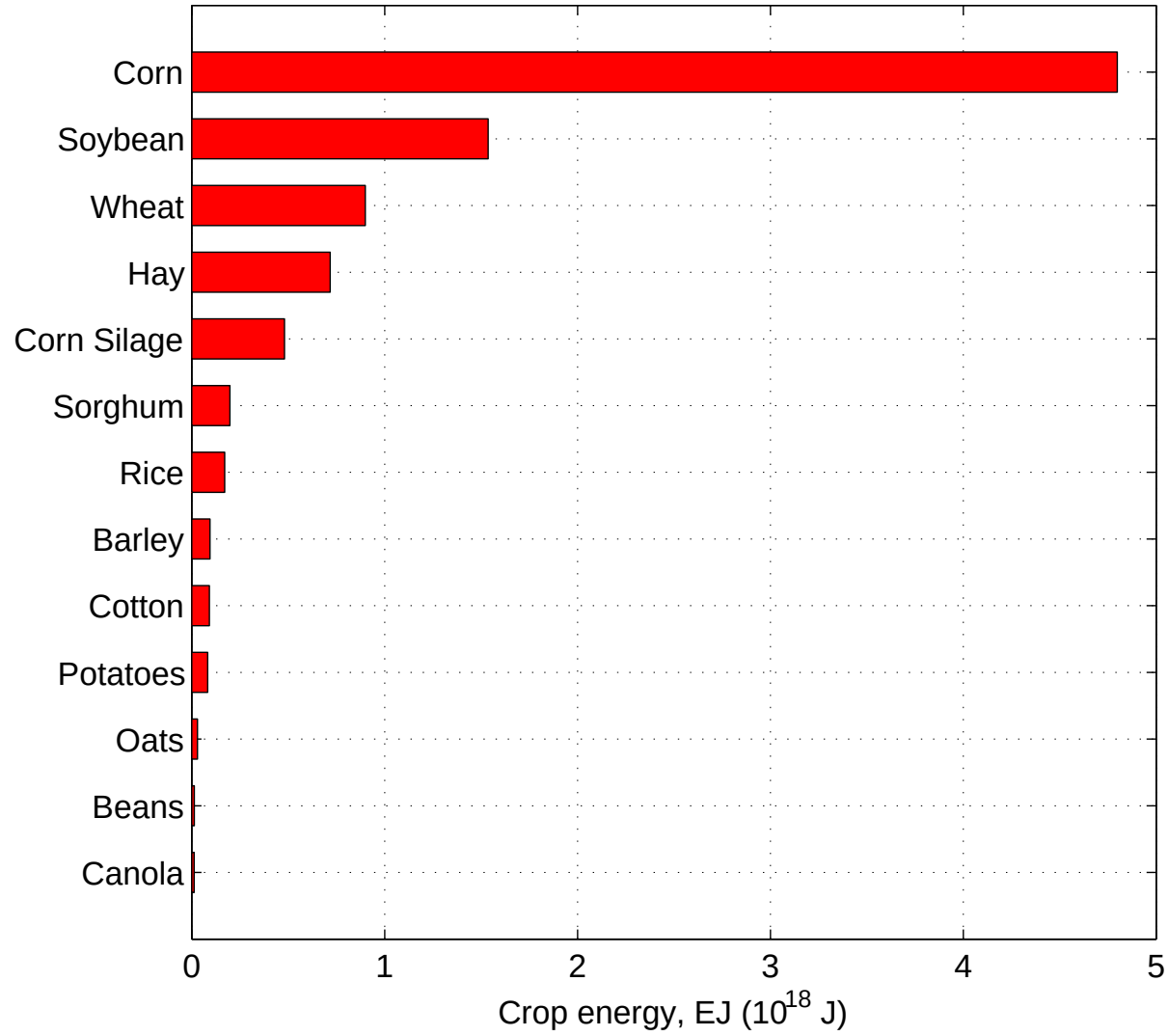
$$\frac{\text{kg harvested seeds}}{\text{kg biomass above ground}}$$

- Root-to-shoot ratio

$$\frac{\text{kg roots at harvest}}{\text{kg biomass above ground}}$$

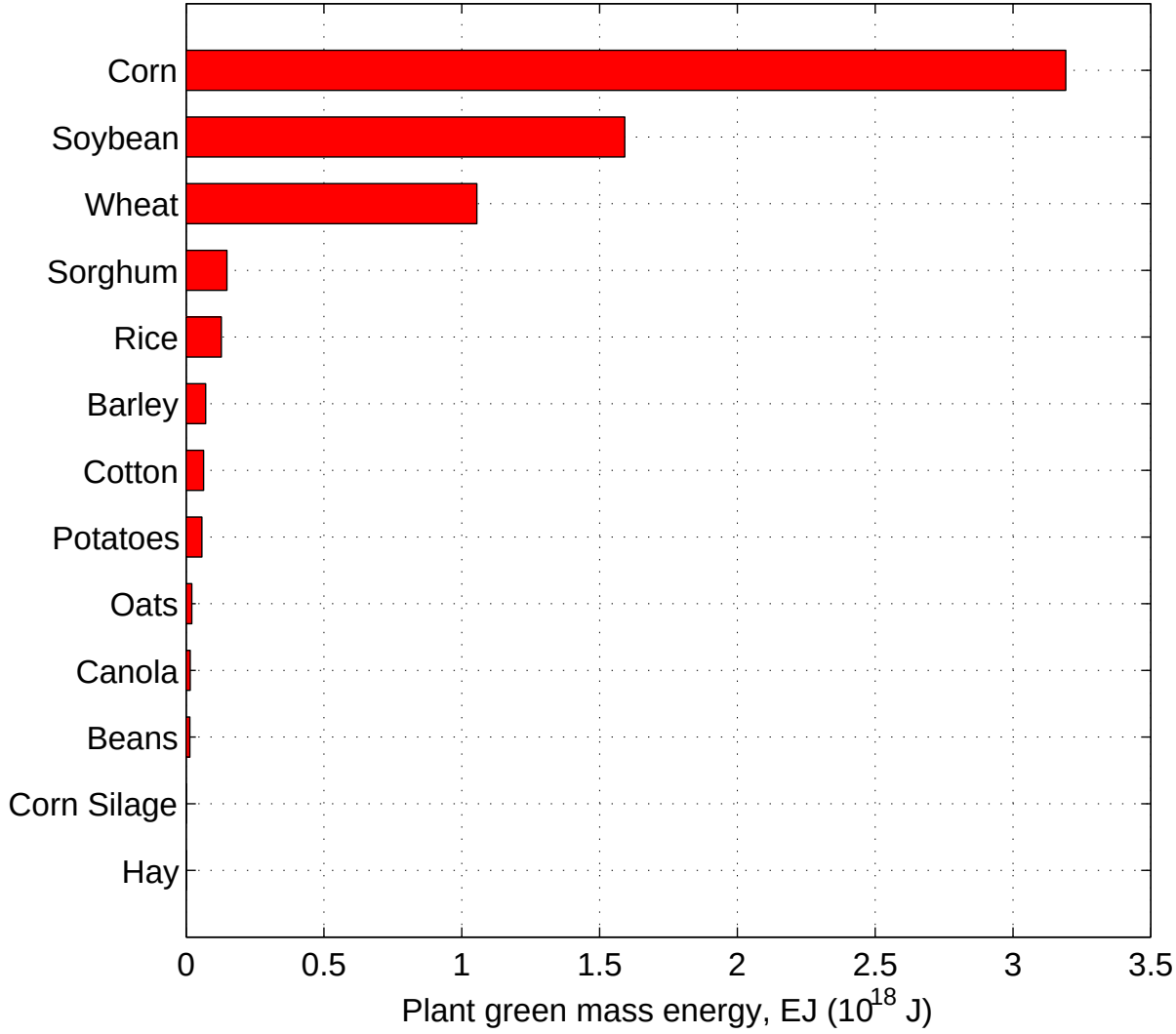
- Moisture contents of crops, above-ground biomass, and roots
- High heating values of plant parts in MJ/kg dry biomass

US Agriculture: Crop Energy



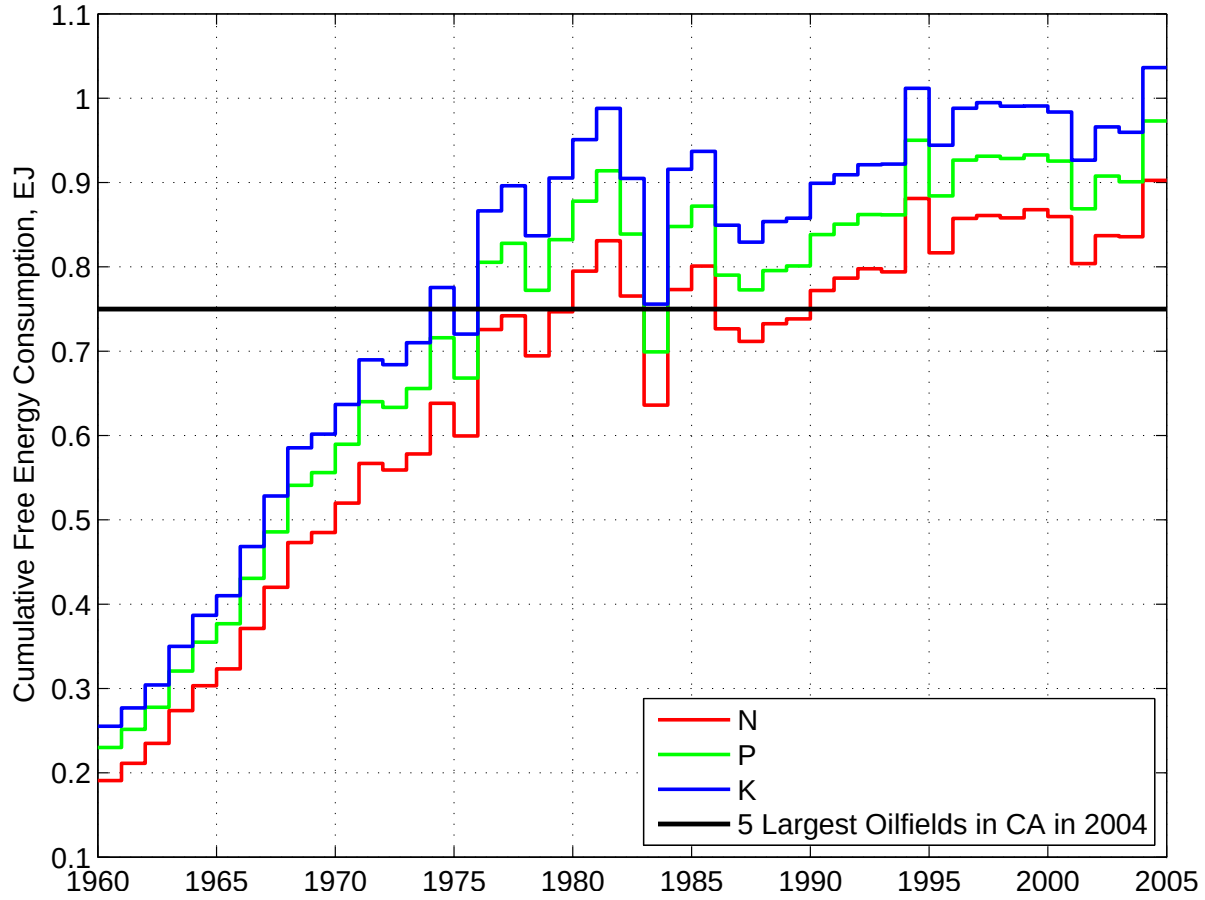
Sources: USDA NASS, Patzek (2006). Total crop energy 9.14 EJ (9 quads)

US Agriculture: Plant - Crop Energy



Total energy in above-ground biomass other than seed 6.35 EJ (6 quads)

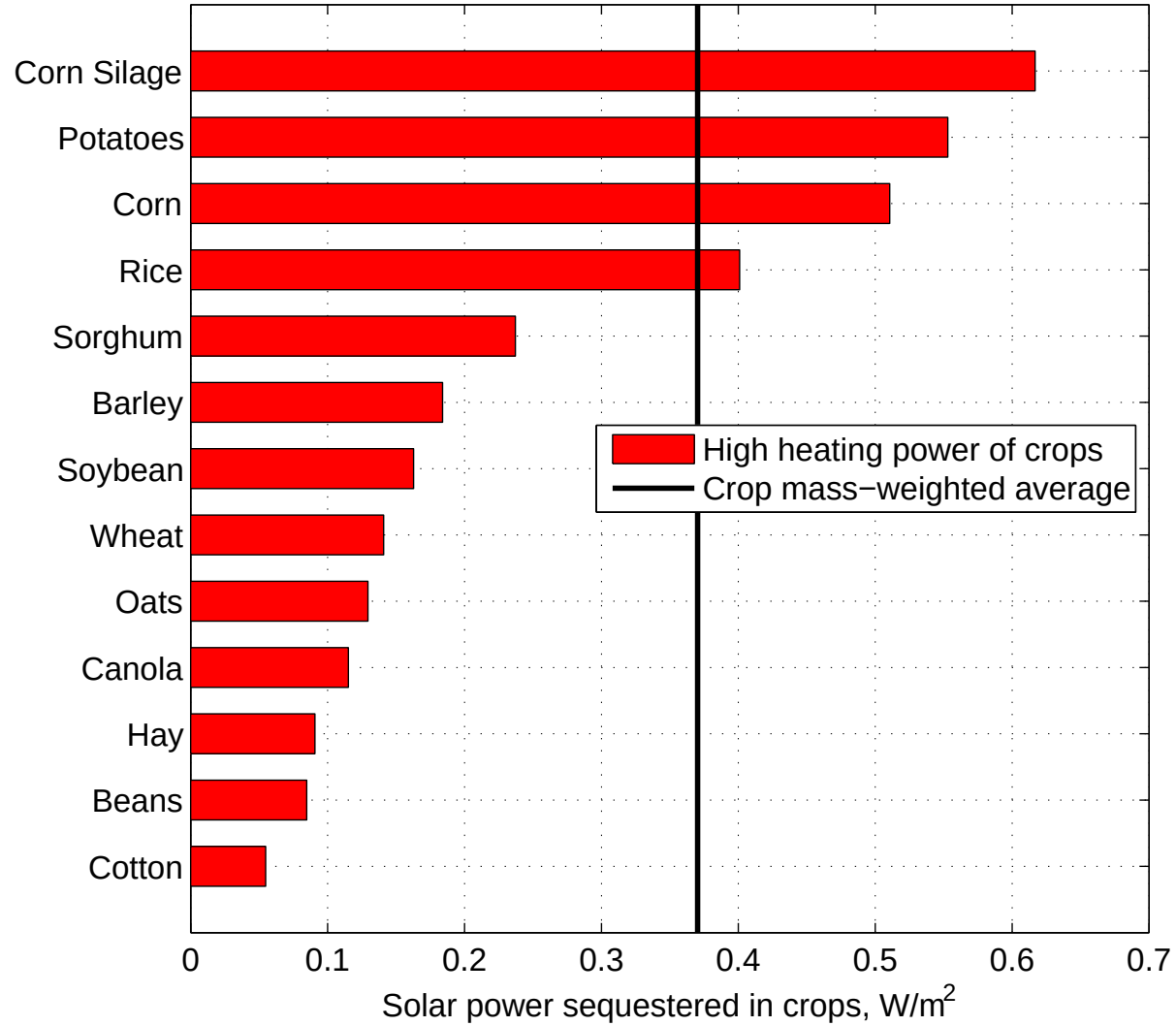
US Agriculture: Fertilizer Energy



Sources: USDA NASS, Patzek (2004)

Oilfields are: South Belridge, Cymric, Kern River, Midway Sunset, and Elk Hills

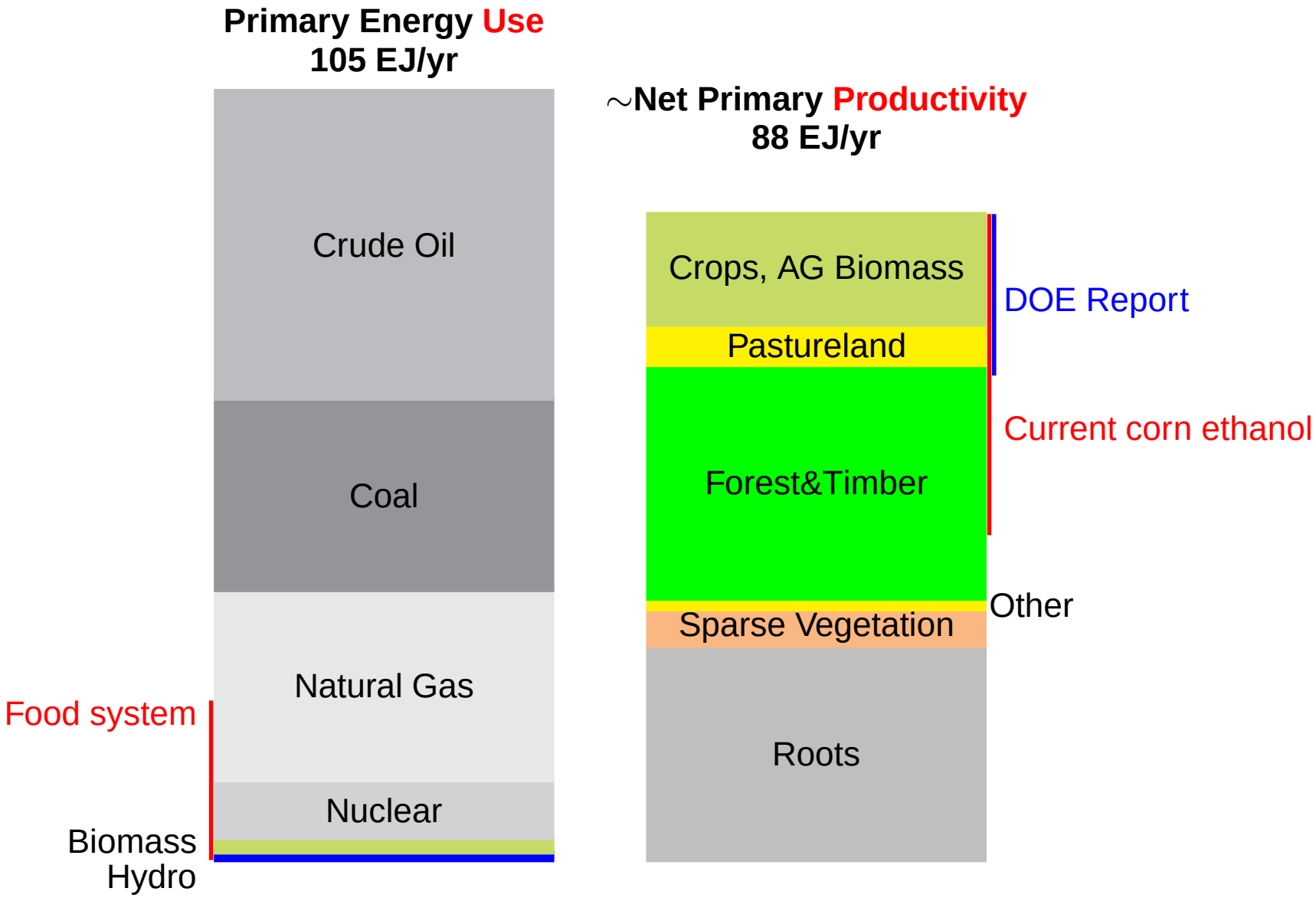
US Agriculture: Power Flux



Sources: USDA NASS, Patzek (2004). Mean crop power flux 0.37 W/m^2

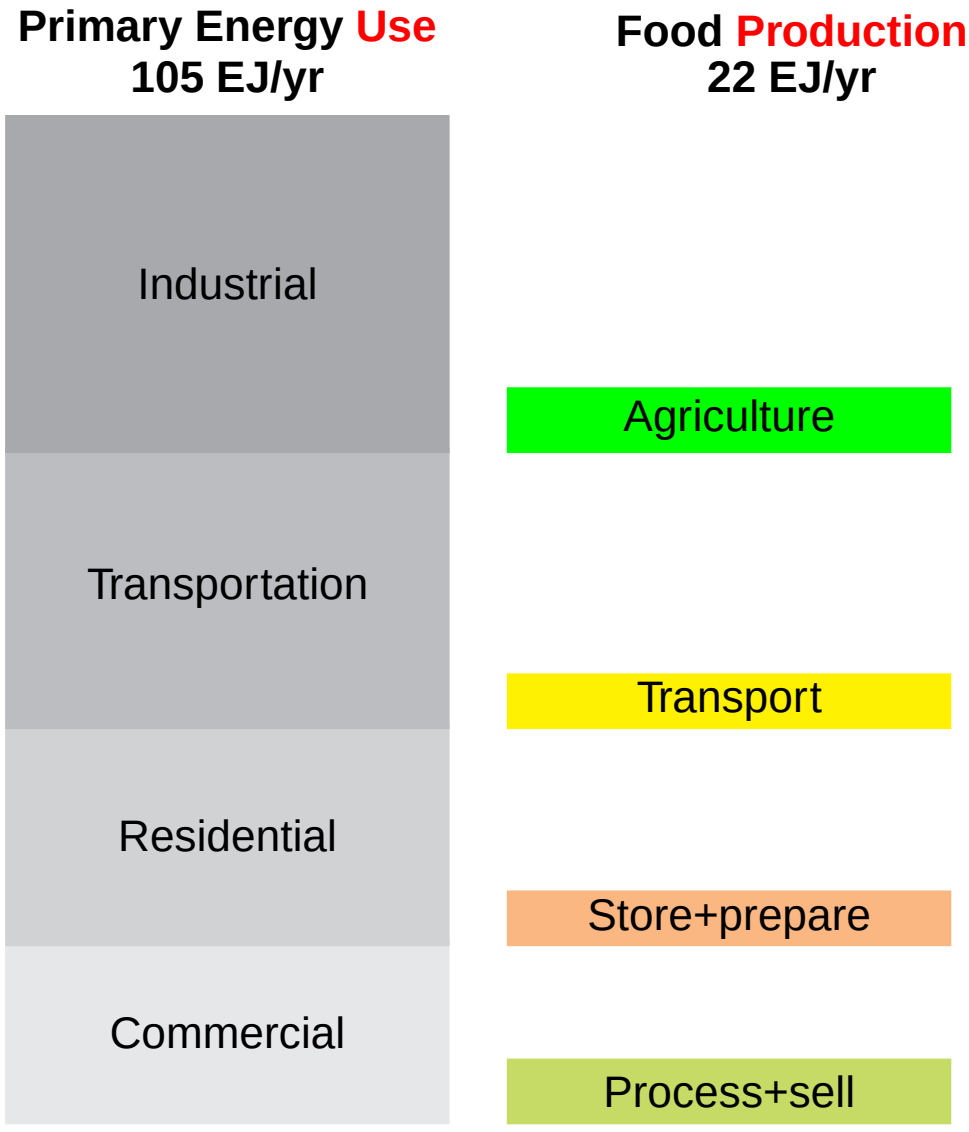
Each person in US uses 11,250 W of primary energy + Imported goods

Net Production of Biomass in US



Sources: USDA, US Forest Service, Patzek, 2006

Energy Use in Agriculture



Sources: USDA; Miller, Environmental Science, 1995, p. 377

Land Use Myths

#5: In 20-50 Years:

- NRDC: 114 million acres for our transportation needs
- Jim Woolsey/George Shultz estimate 60 million acres
- Khosla: 55 million acres

Source: Vinod Khosla, *Biofuels: Think outside the Barrel*, April 2006

Note the huge discrepancy between the estimates above, and the 850 - 1,500 million acres necessary to produce 130 billion gallons of ethanol for more than 1 year

Cellulosic Ethanol Claims

"...My message for you today is this: Cellulose ethanol is ready to go.

Based on Iogen's experience with its demonstration facility, we are ready to break ground on a commercial-scale biorefinery in the summer of 2007, and plan to be supplying ethanol to commercial markets by 2009. After the first plant is built, we anticipate the development of a multi-plant, multi-billion-gallon industry."

Testimony of JEFF PASSMORE
Executive Vice President, Iogen Corporation
Before the Full Committee on Agriculture, June 29, 2006

Do These Claims Make Sense?

Production of cellulosic ethanol requires:

- Steam pretreatment/ball milling/acid attack step to liberate cellulose and hemicelluloses from lignin,
- Hydrolysis step, to convert the carbohydrates to simpler sugars,
- Yeast or bacterial fermentation step, to yield dilute ethanol,
- Ethanol separation step (distillation, drying)

After 50 years and $1 billion of R&D, only one pilot plant (Iogen Corp.) is operating, producing about 160 thousand gallons of ethanol per year, 1/6 of its planned capacity

Do These Claims Make Sense?

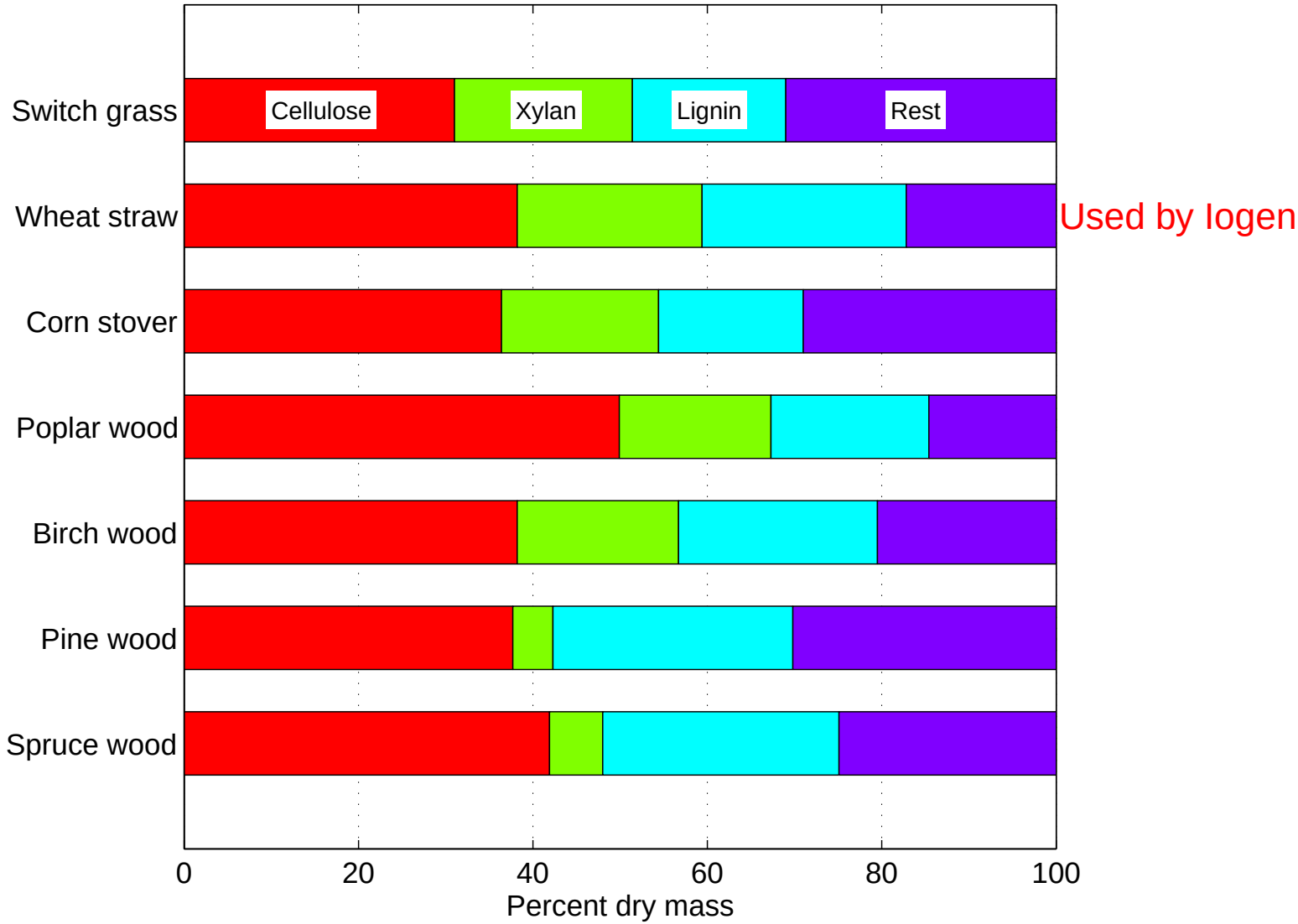
In addition to cutting most living plants in the US, to obtain 130 billion gallons of ethanol by 2030

- The Iogen plant must be scaled up 81,000 times. That's 8,100,000%
- In human history, such scale up has never occurred within 20 years, even if a good technology existed
- We do not have a cellulosic technology to scale up

Cellulosic Ethanol Facts. . .

Brief Explanation

Biomass Composition. . .

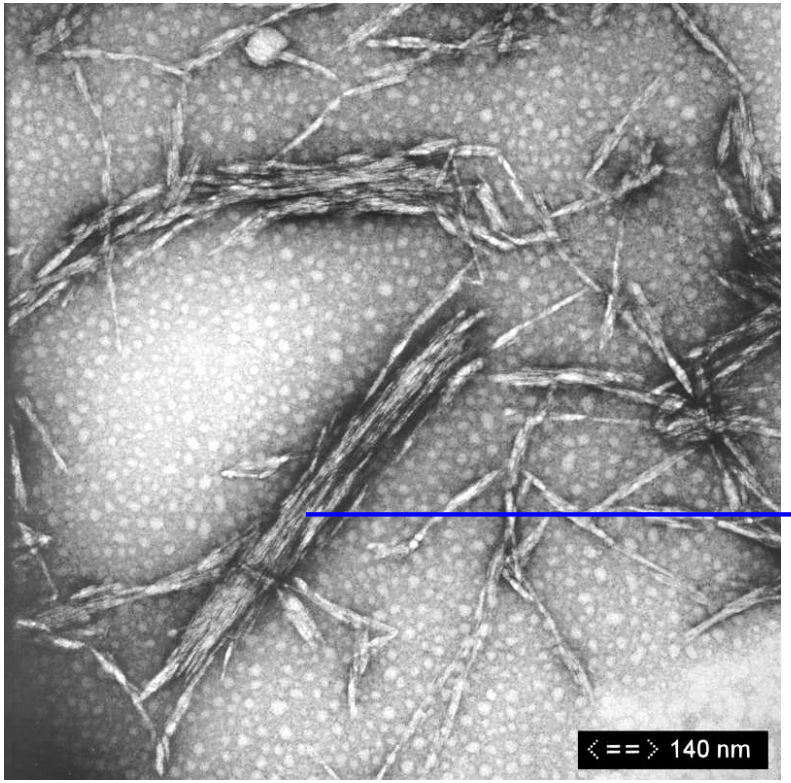


Used by logen

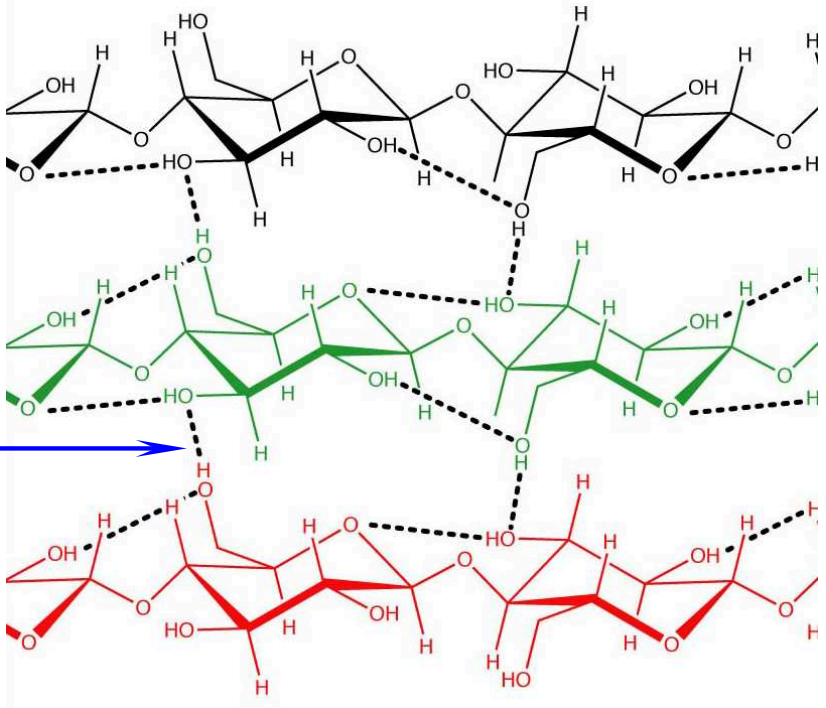
Source: WISELOGEL, A., *Biomass feedstock resources and composition*, 1996

3 Billion Years of Cellulose

Cellulose makes cell walls in plants and is very tough to break



Crystalline cellulose

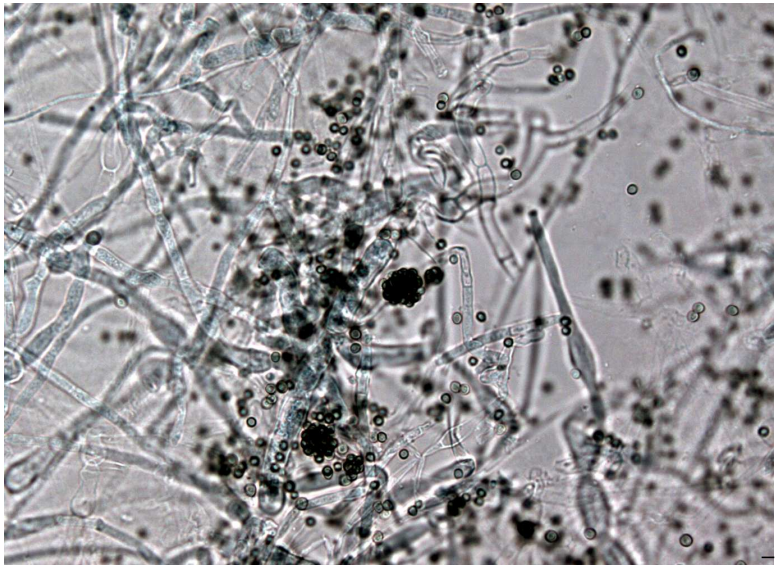


β-glycosidic bonds

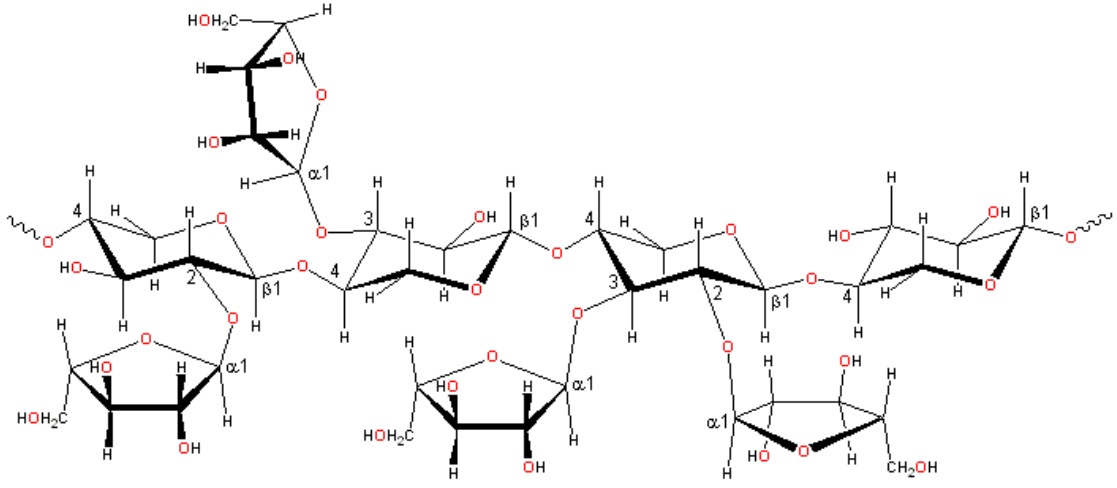
Fungus *Trichoderma reesei*

Some 92 enzymes can decompose cellulose to glucose, e.g.:

- endo-1-β-1,4-glucanase (C_x) converts randomly amorphous cellulose to cellobiose
- β-1,4-glucan cellobiohydrolase (CBH) removes cellobiose from non-reducing ends of cellulose chains
- C_x + CBH + β-glucosidase hydrolyze crystalline cellulose
- β-glucosidase hydrolyzes cellobiose to glucose



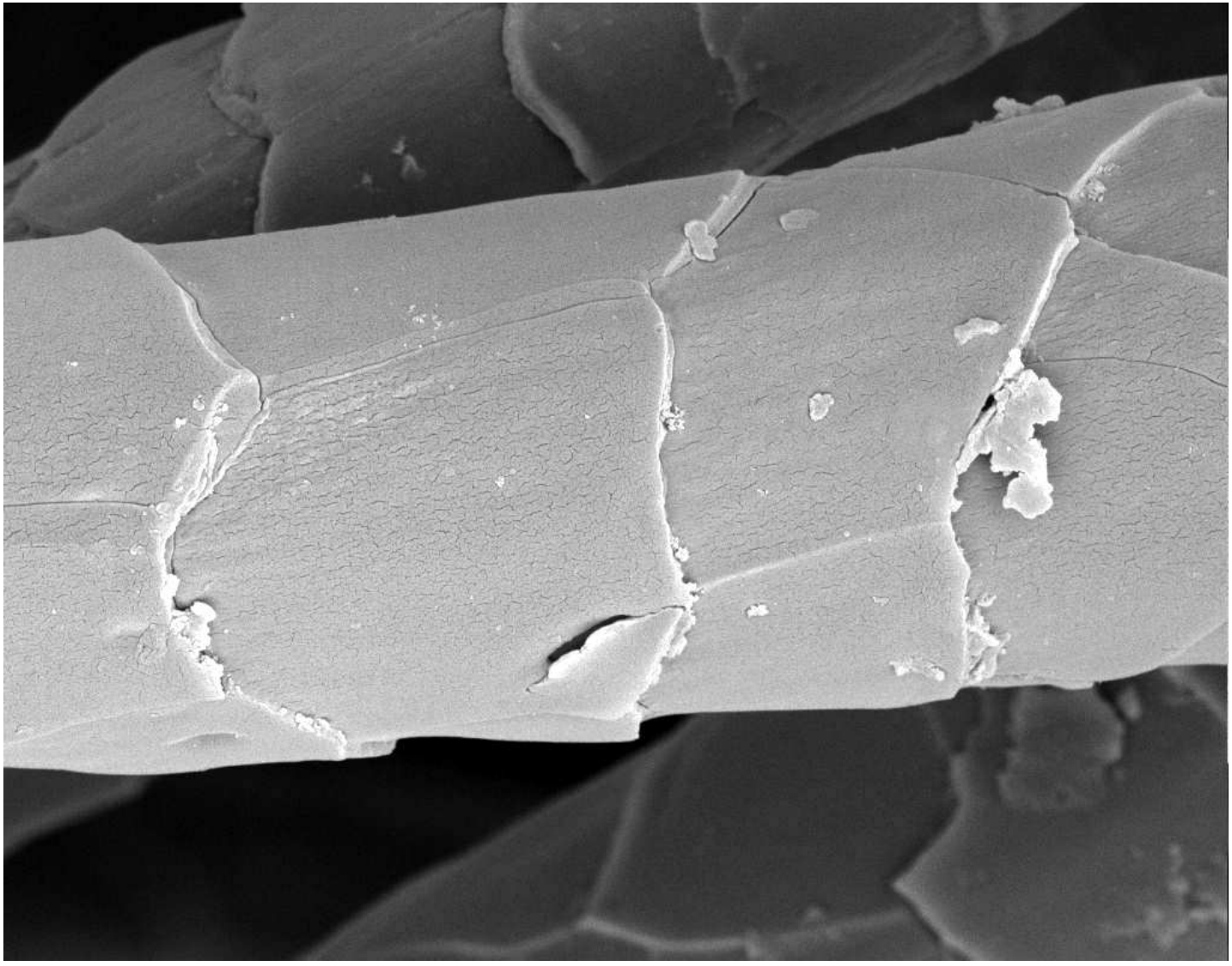
Hemicellulose. . .



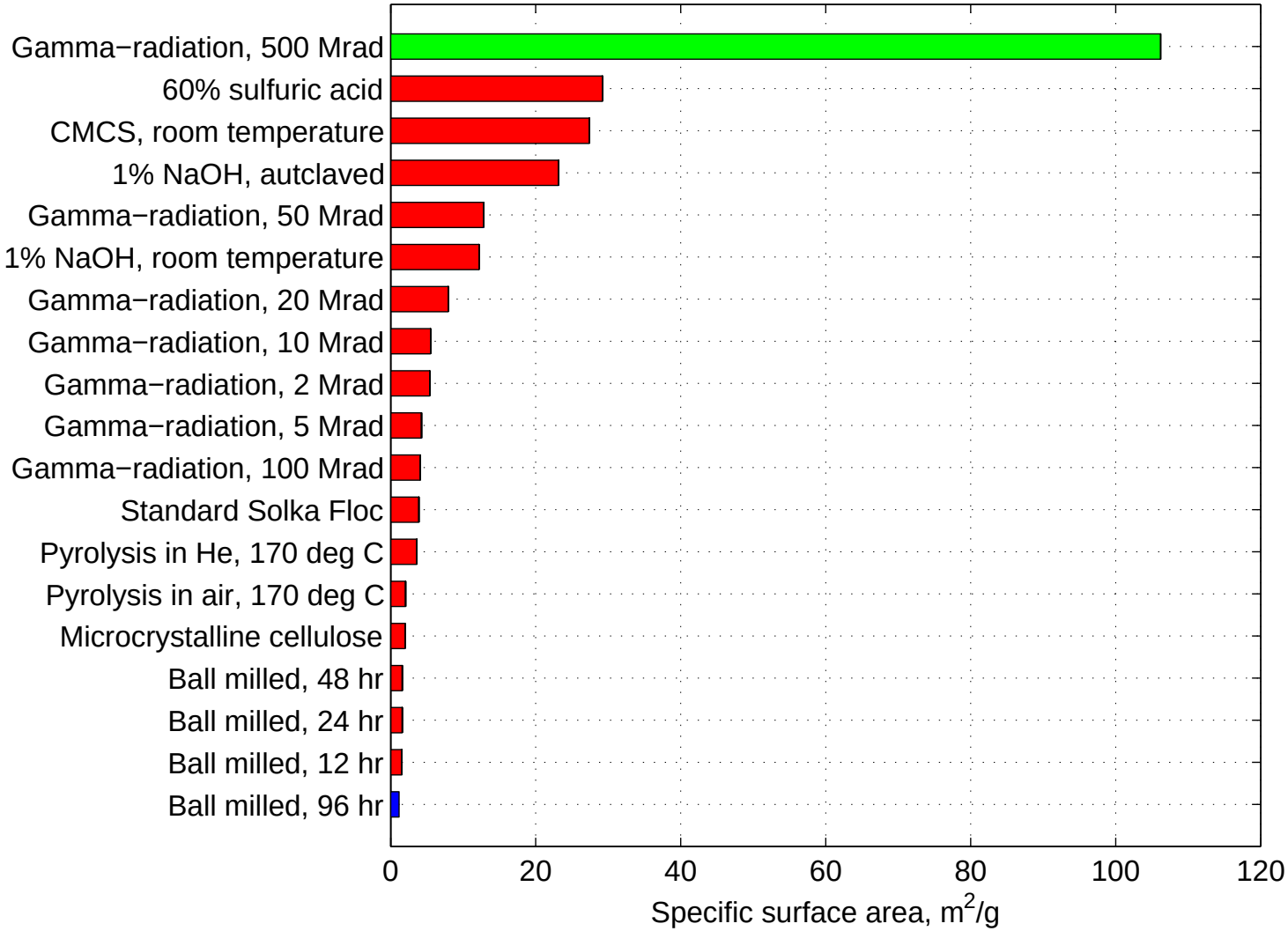
- In hardwoods and annual plants hemicellulose consists mostly of xylans and glucomannans
- Xylans hydrolyze to 5-atom sugars, xyloses, that *cannot* be fermented to ethanol by standard yeast
- Endoxylanase and endomannanase enzymes act synergistically to degrade hemicellulose
- Further hydrolysis is accomplished with β - xylosidase, mannosidase, and glucosidase

Enzymes Are in Water…

…They Are Slow to Attack Cellulose Fibers

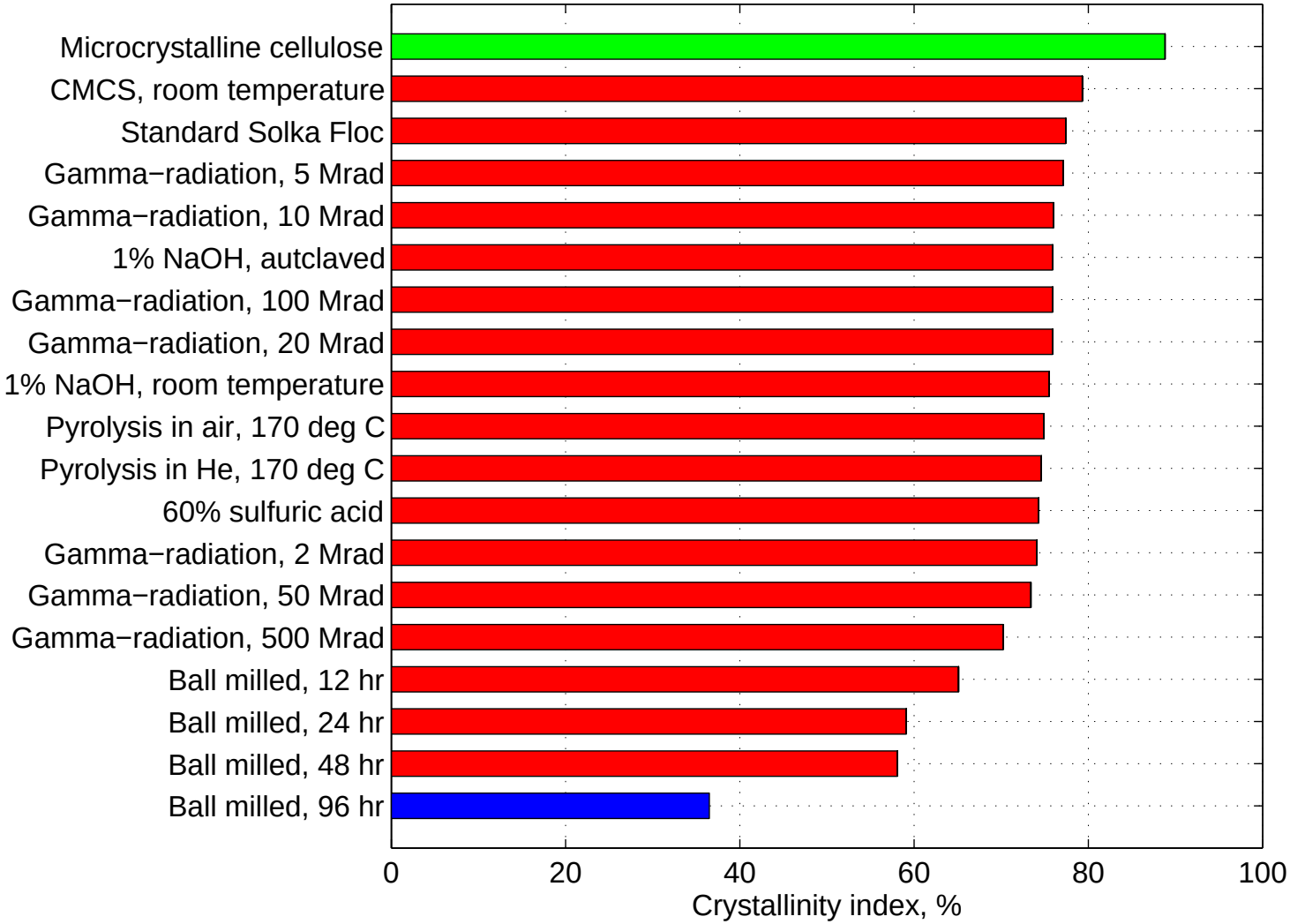


Increase Specific Surface Area...



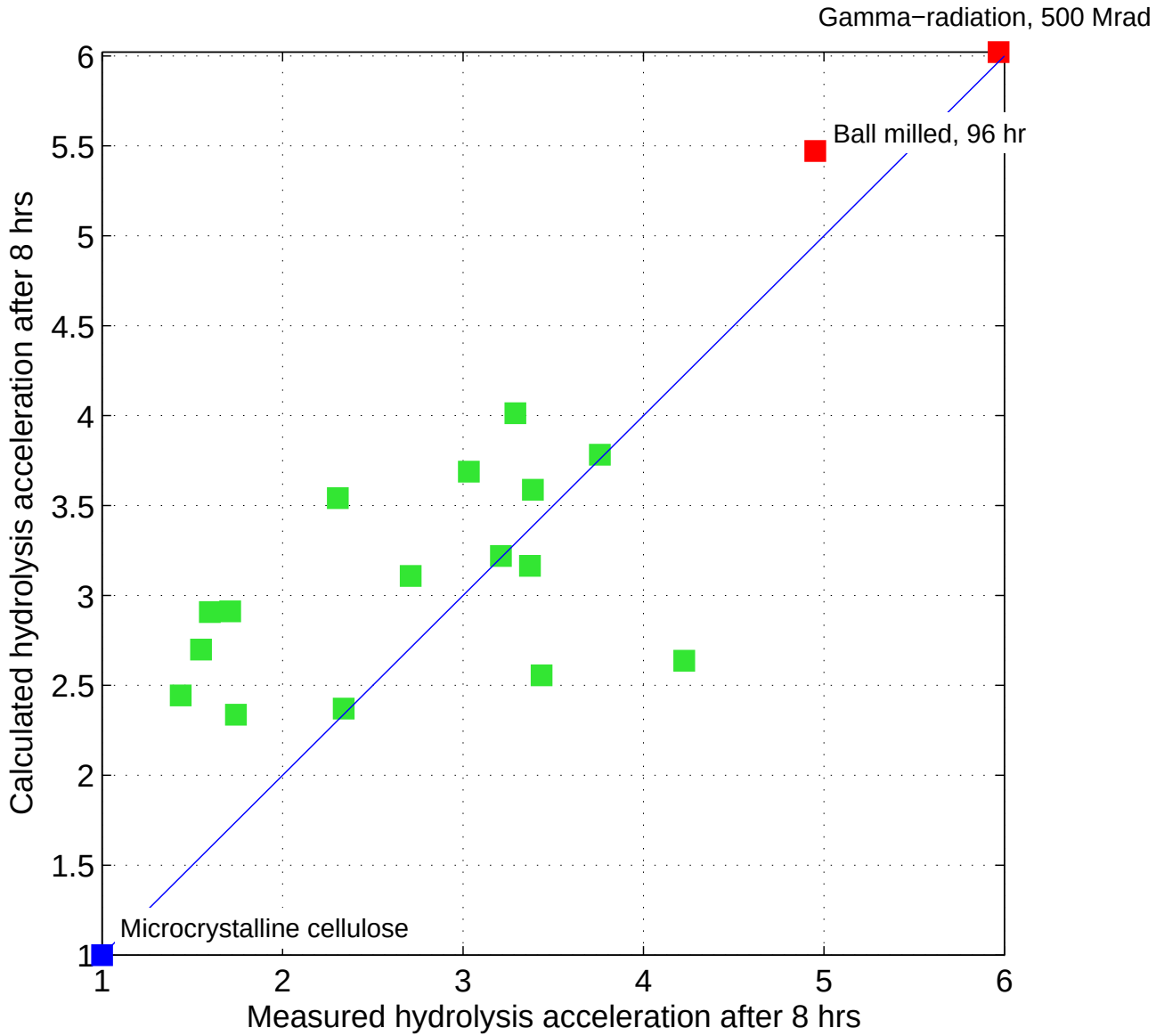
Source: FAN, L. T. and LEE, Y.-H. and BEARDMORE, D. R., 1981

Smash Cellulose Crystals. . .



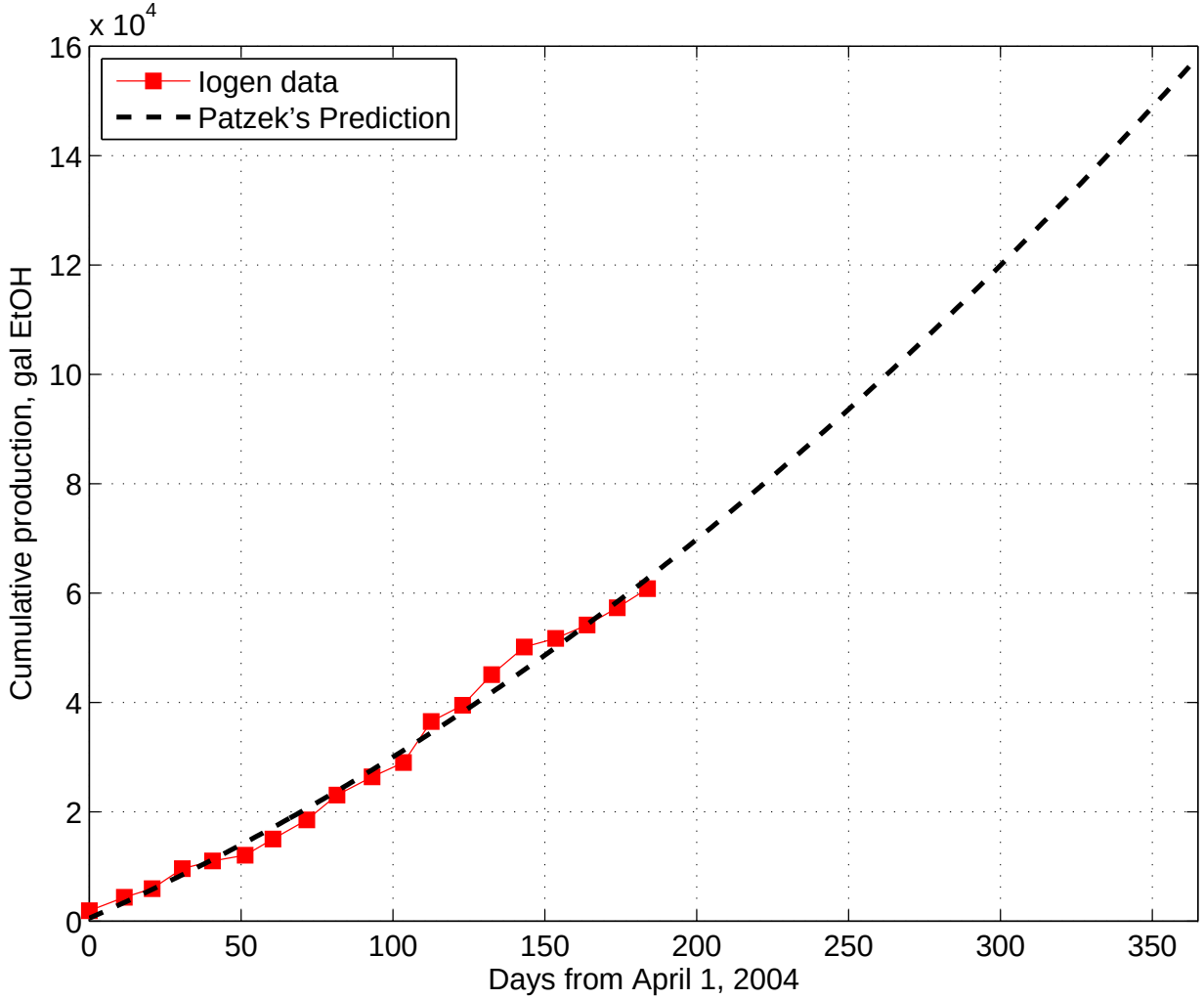
Source: FAN, L. T. and LEE, Y.-H. and BEARDMORE, D. R., 1981

Accelerate Initial Rate. . .



Source: FAN, L. T. and LEE, Y.-H. and BEARDMORE, D. R., 1981

Iogen Ottawa Plant - 6.7 BOE/day



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

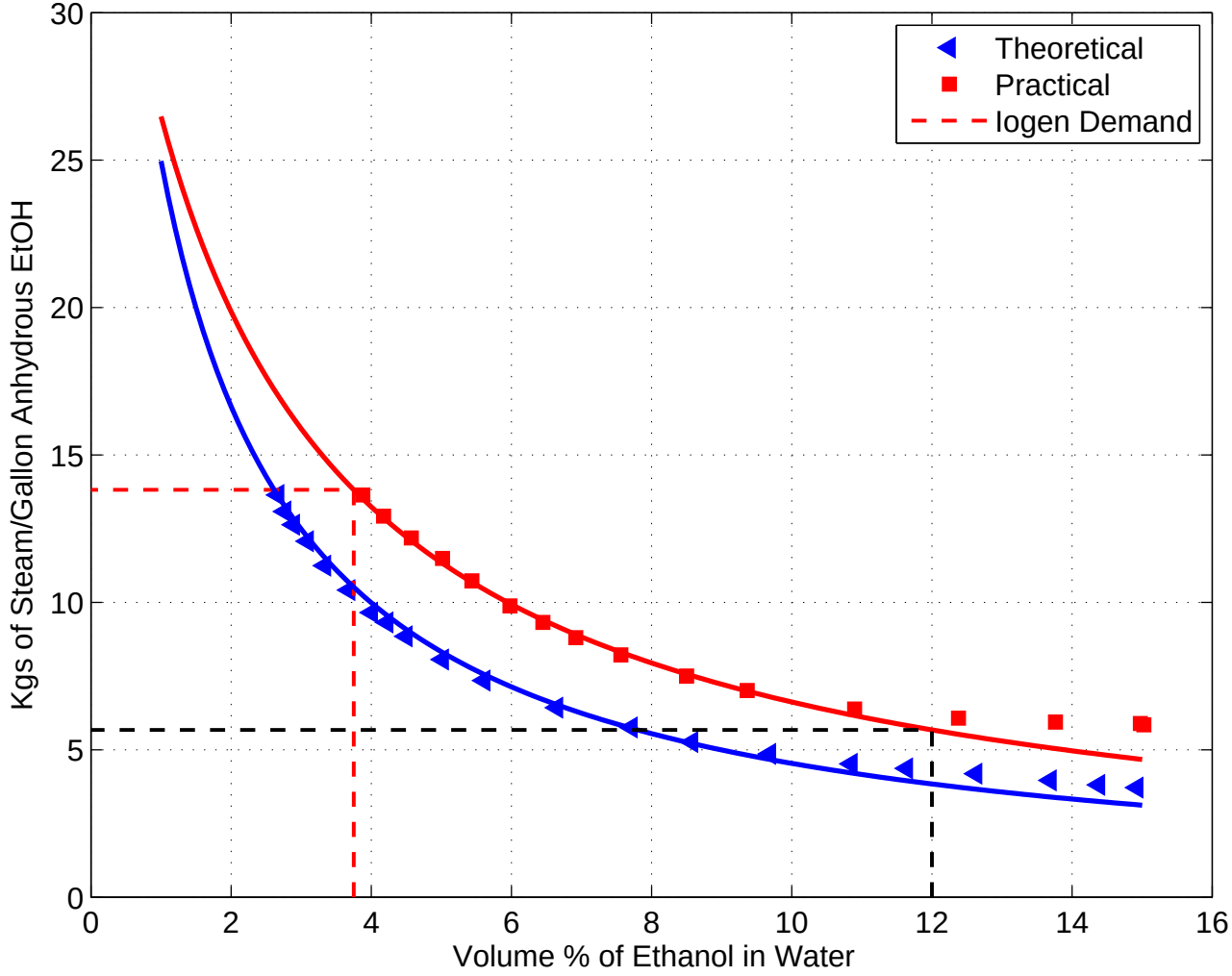
Iogen Ottawa Plant - Specifications

Deduced production specification:

- 158,000 gallons/year of anhydrous ethanol
- 10 bbl EtOH/day = 6.7 bbl of equivalent gasoline/day
- $2 \times 52{,}000 = 104{,}000$ gallons of fermentation volume
- Ratio of 1.5 gallon EtOH/gallon fermenter-year
- Assume 7-day batches + 2-day cleanups
- Then there is 3.7% of alcohol in water in a batch

One of two 52,000 gallon enzyme fermenters. Source: MAURICE HLADIK, Director of Marketing, Iogen Corp.

Iogen Ottawa Plant - Steam

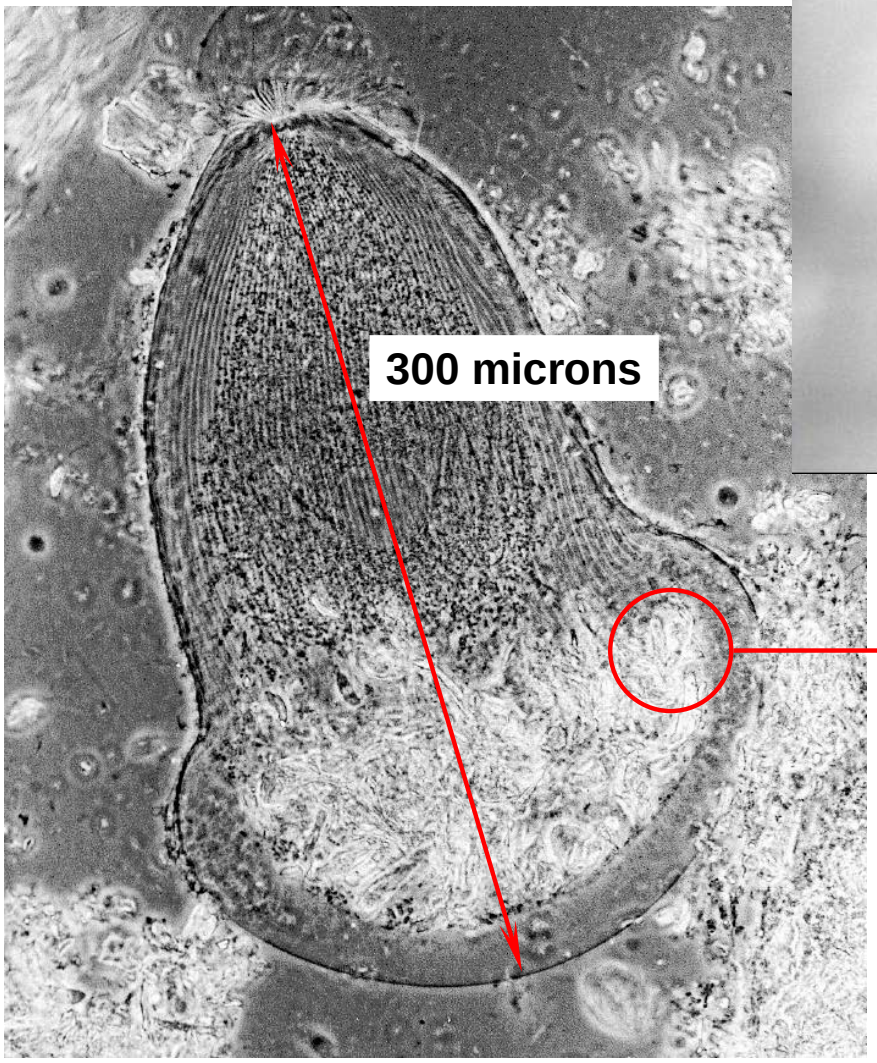


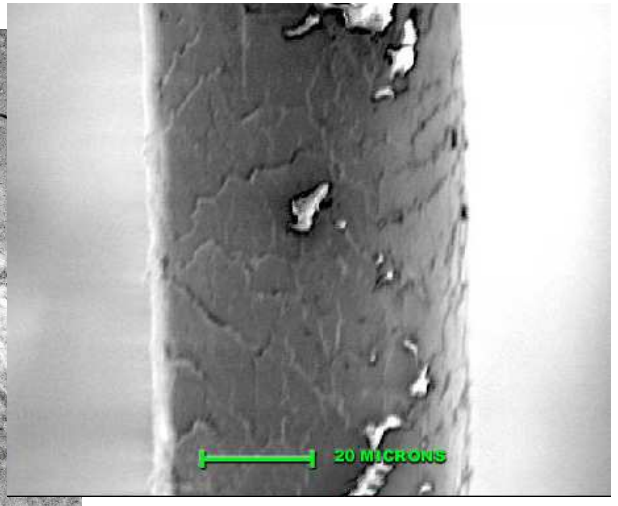
Source: K. A. JACQUES et al., *The Alcohol Textbook*, Nottingham University Press; 4th revised edition (October 15, 2003)

Iogen Ottawa Plant - Summary

- One would need 67,000 Iogen Ottawa plants to replace petroleum refineries in Texas alone
- Industrial cellulosic ethanol technology does not exist
- Iogen's Ottawa plant is a tiny, inefficient facility that produces 6.7 barrels of gasoline equivalent per calendar day with
  - Low ethanol yields
  - Dilute ethanol solutions after each batch
  - Lack of scalability
- There are important physical reasons for this failure: slow, inefficient cellulose hydrolysis despite costly preprocessing, inefficient fermentation of pentoses, and distillation of dilute beer

Termite-Bacteria Symbiosis

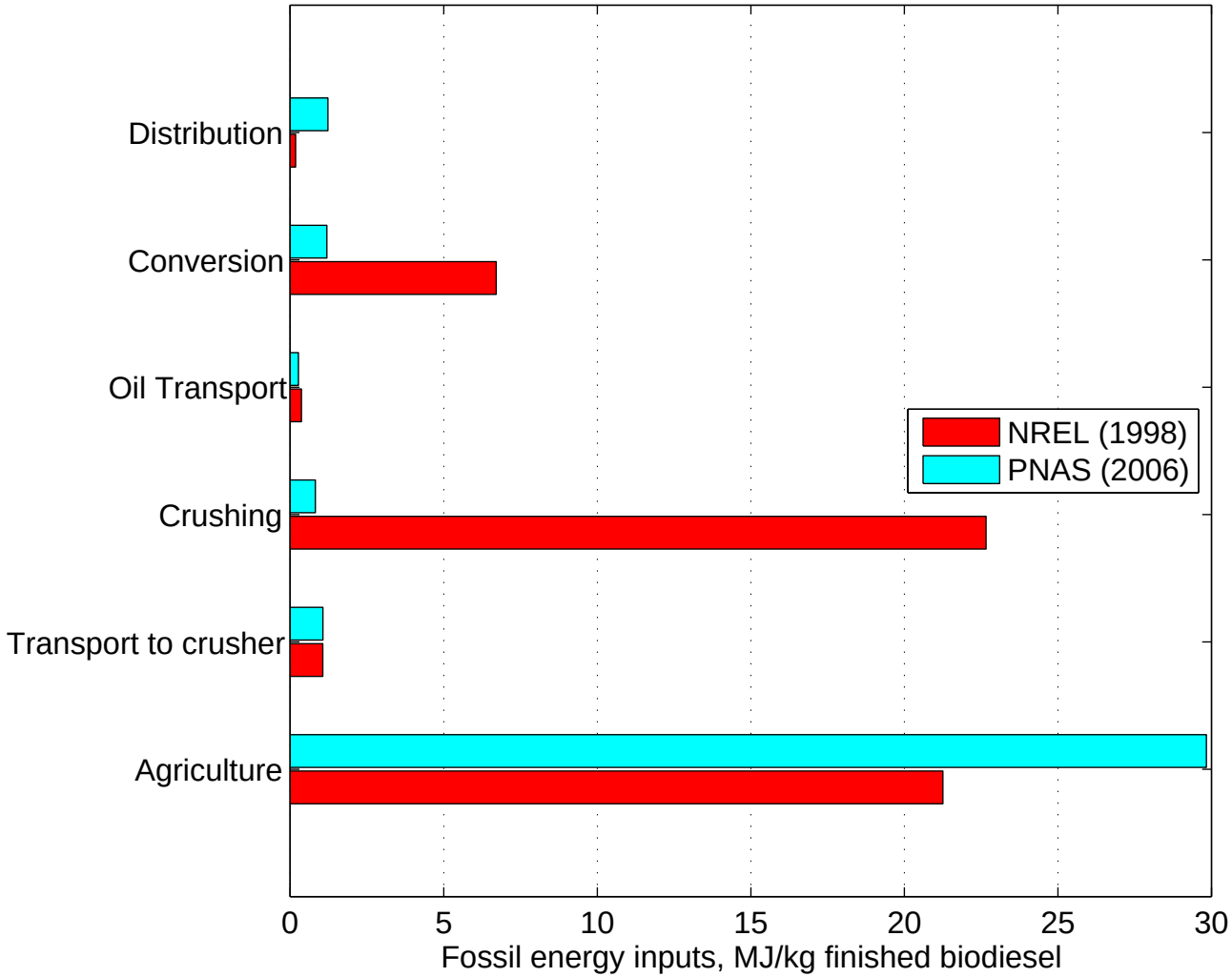




<50 micron-wood particles

Trichonympha bacterium. In the lower portion of the cell, you can see wood particles being digested. Source: www.ucmp.berkeley.edu/protista/termiteprotists.html

Fossil Energy Cost of Biodiesel



Biodiesel has 40 MJ/kg of energy. Corrected NREL estimates fossil energy inputs is 52 MJ/kg, and uncorrected PNAS estimate is 34 MJ/kg

Bottom Line. . .

Another problem with subsidies. . . is that they simply misinform us about the cost of our behavior. . . . The subsidy certainly does a lot of good for the folks who sell ethanol, especially agribusiness giants, such as Archer Daniels Midland, who are nicely situated to lobby Congress for more subsidies. Most people think it is wrong for the government to lie to its citizens, but there's no other way to portray ethanol subsidies: Your government, by distorting the price you pay so it doesn't reflect real costs, is lying to you.

Subsidies are the wrong road to biofuels, Professor Michael O'Hare, Goldman School of Public Policy at UC Berkeley, San Francisco Chronicle, 7/30/2006