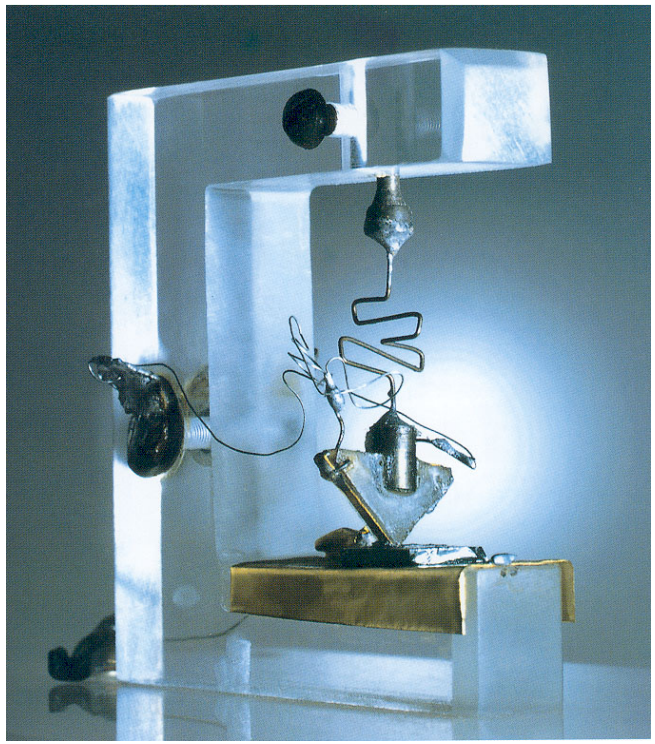
Development of Cellulosic Biofuels

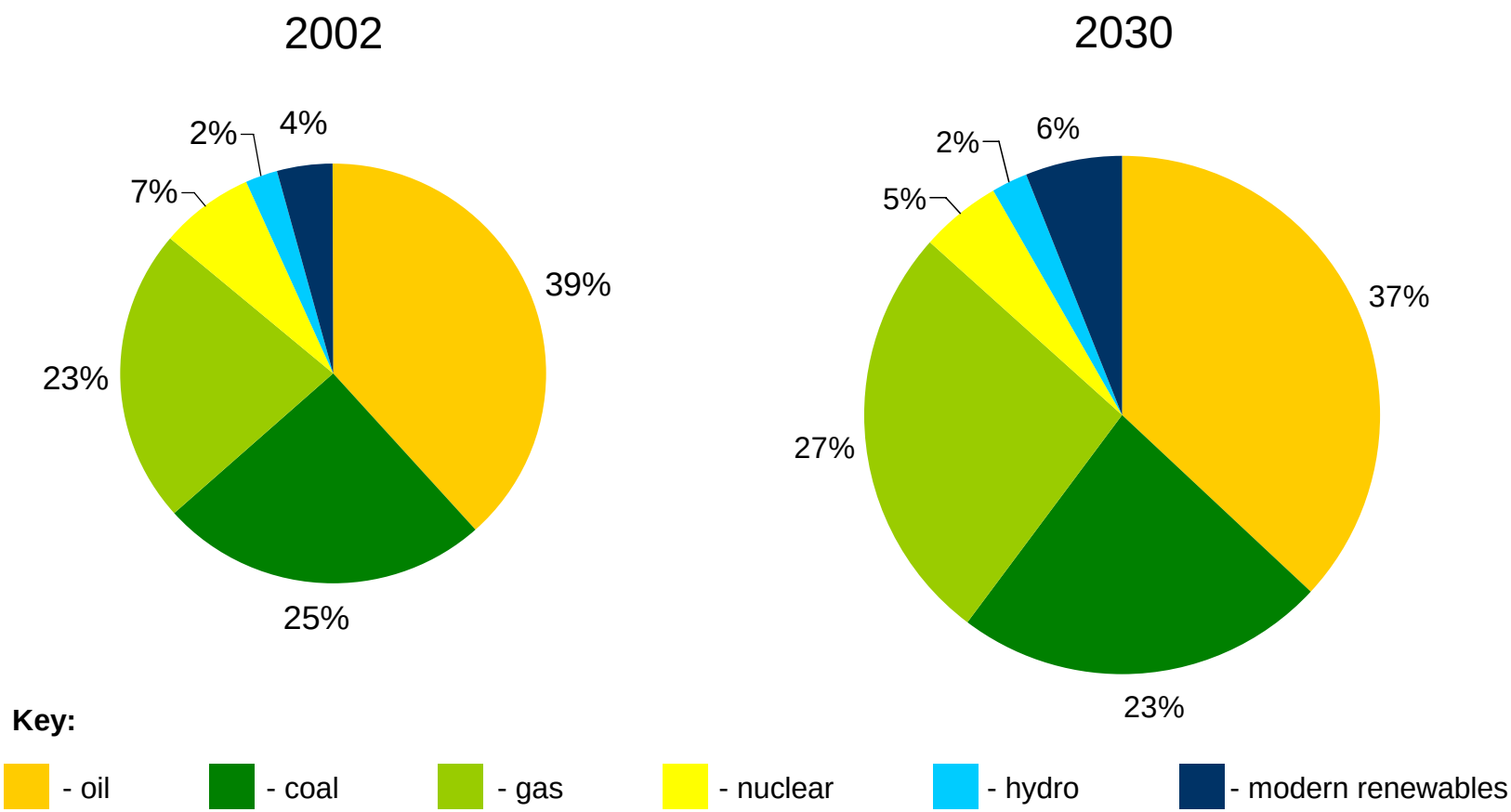


Chris Somerville
Energy Biosciences Institute
UC Berkeley, LBL, University of Illinois

Current and predicted energy use

Current use 13 TW

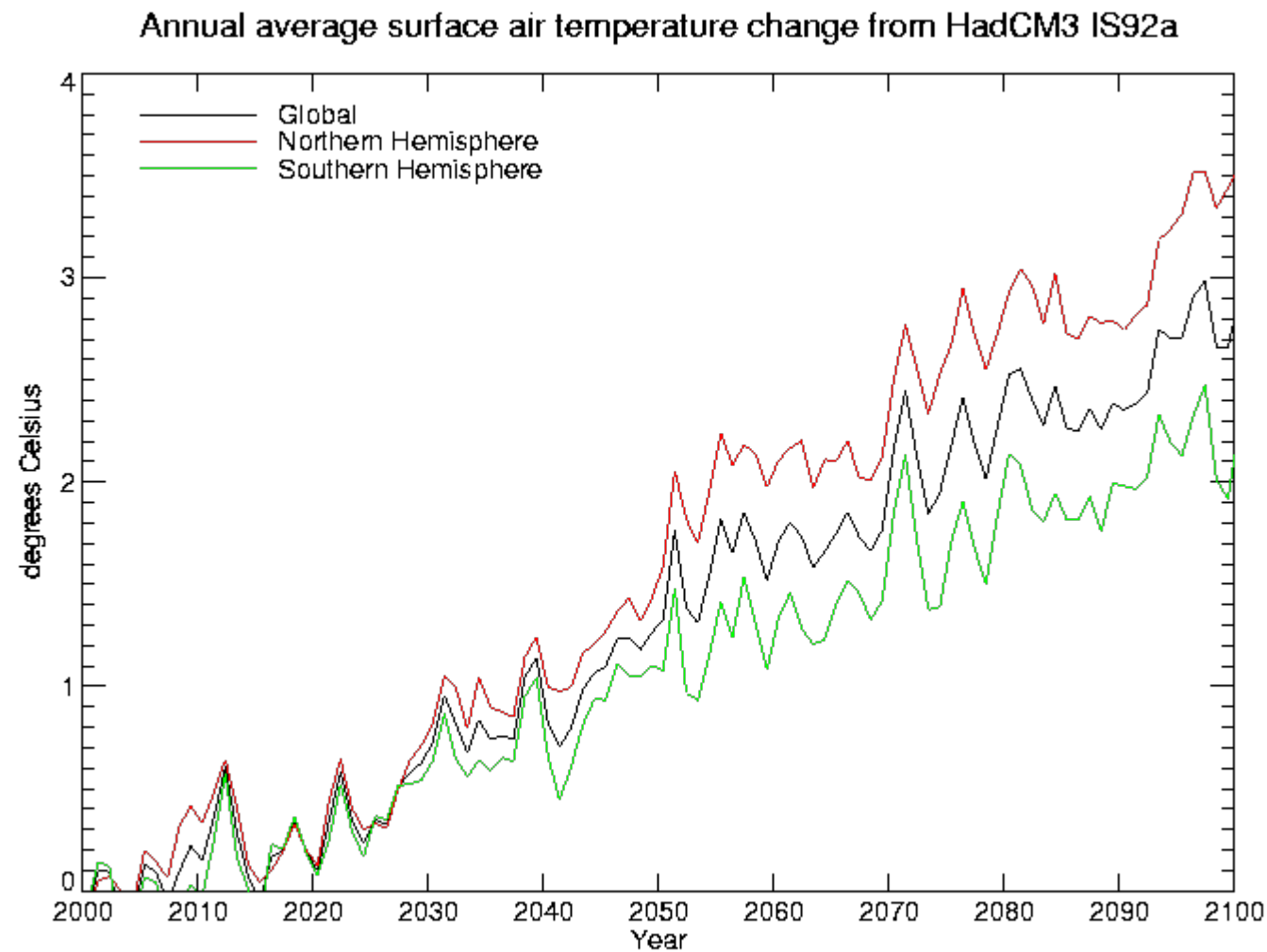
Global Primary Energy Supply by Fuel:*



* - excludes traditional biomass

Source: IEA 2004 & Jim Breson

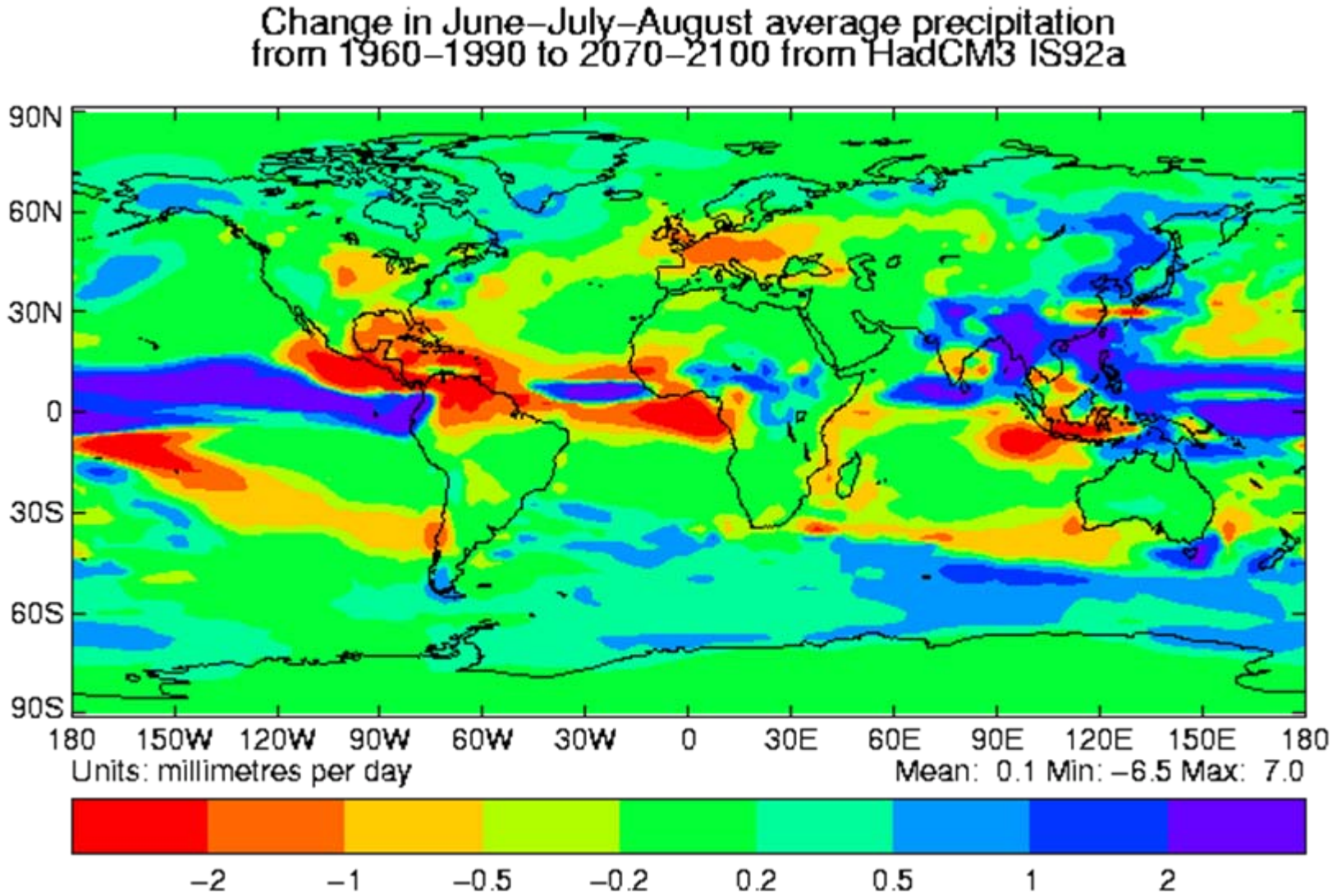
Predicted increase in global mean temperature due to CO_2 accumulation



Hadley Centre for Climate Prediction and Research, The Met. Office

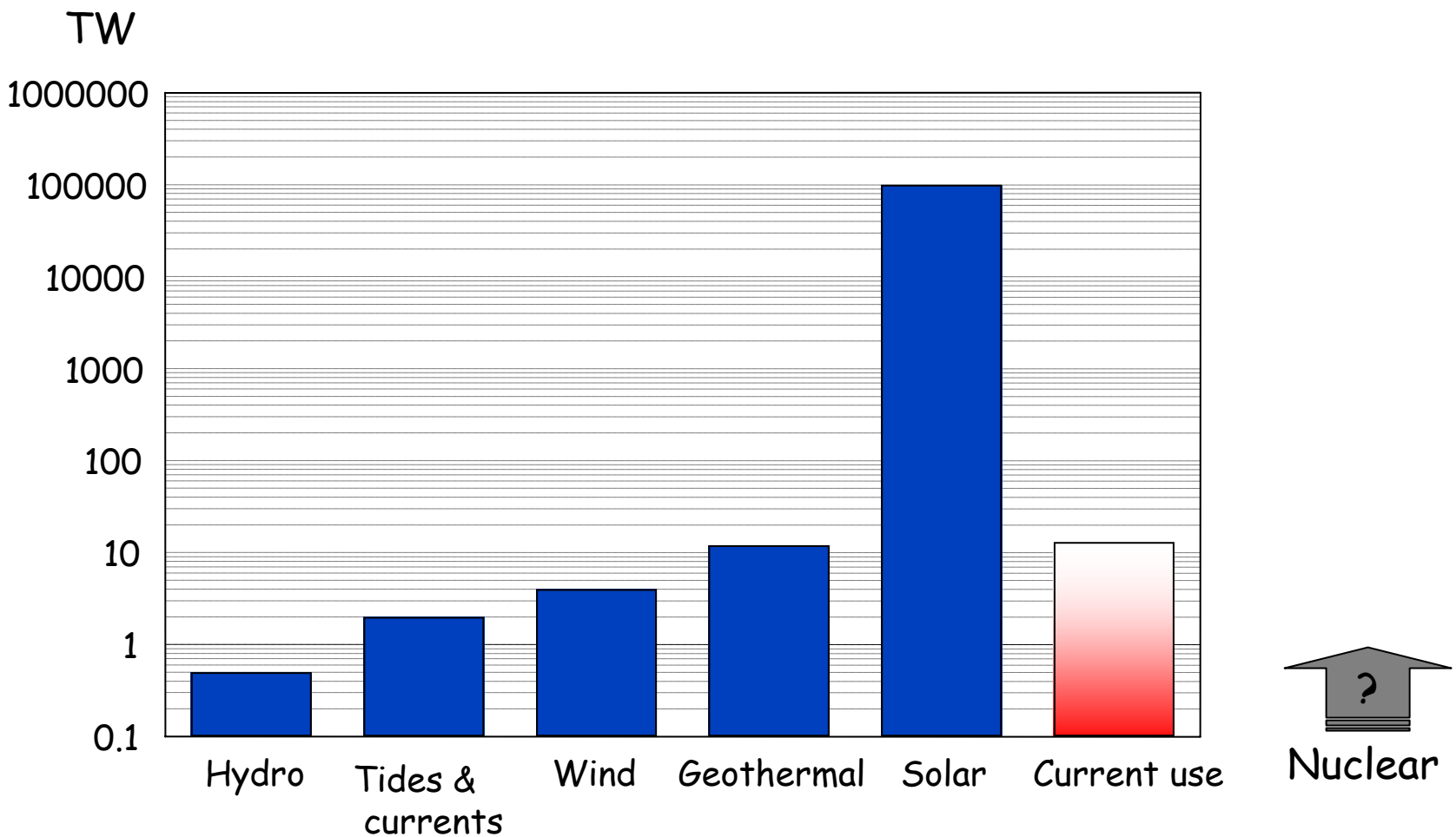
www.metoffice.com/research/hadleycenter

Predicted effects on rainfall



www.metoffice.com/research/hadleycenter

Potential of carbon-free energy sources



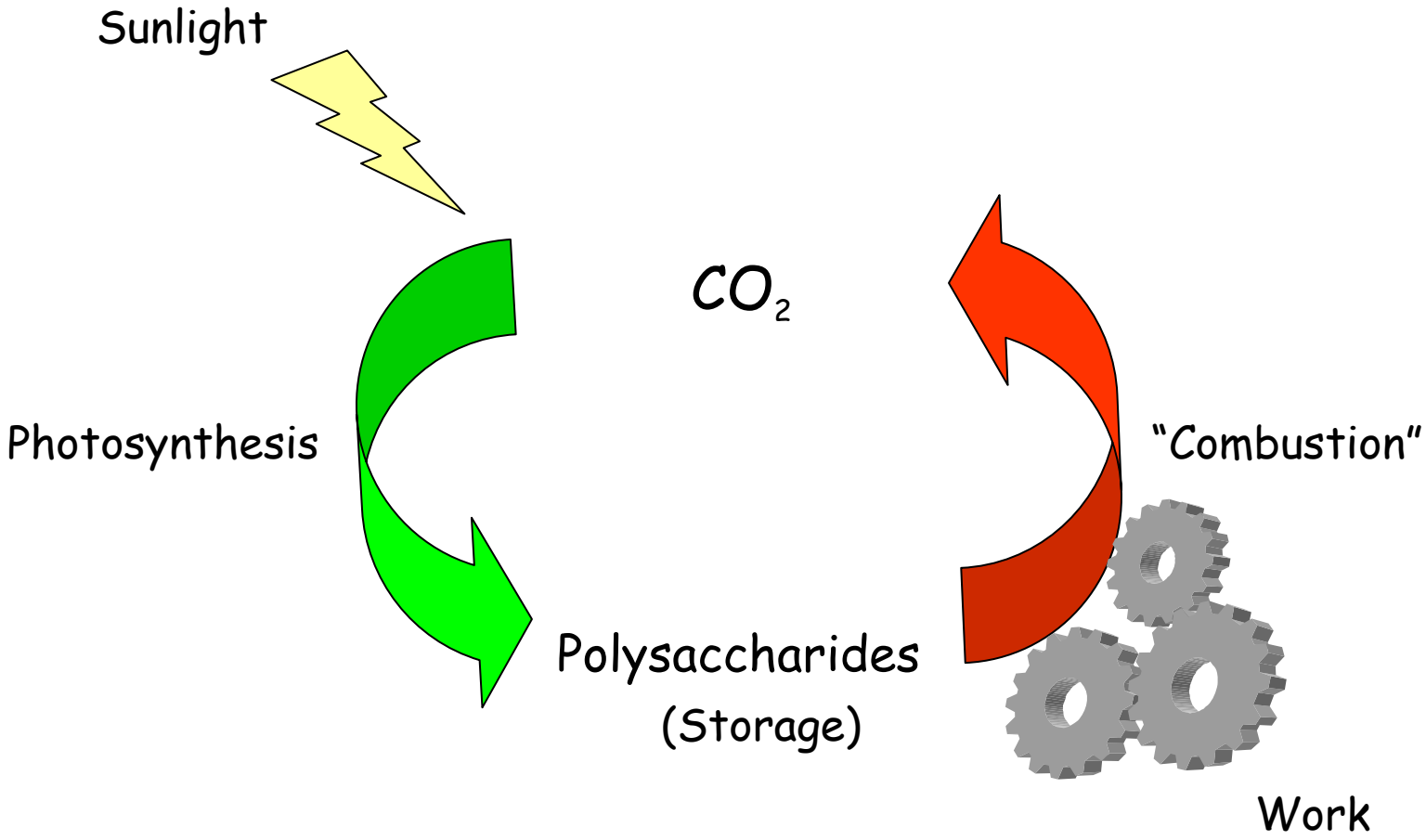
From: Basic Research Needs for Solar Energy Utilization, DOE 2005

~26,000 km^2 of photovoltaic devices would meet US energy

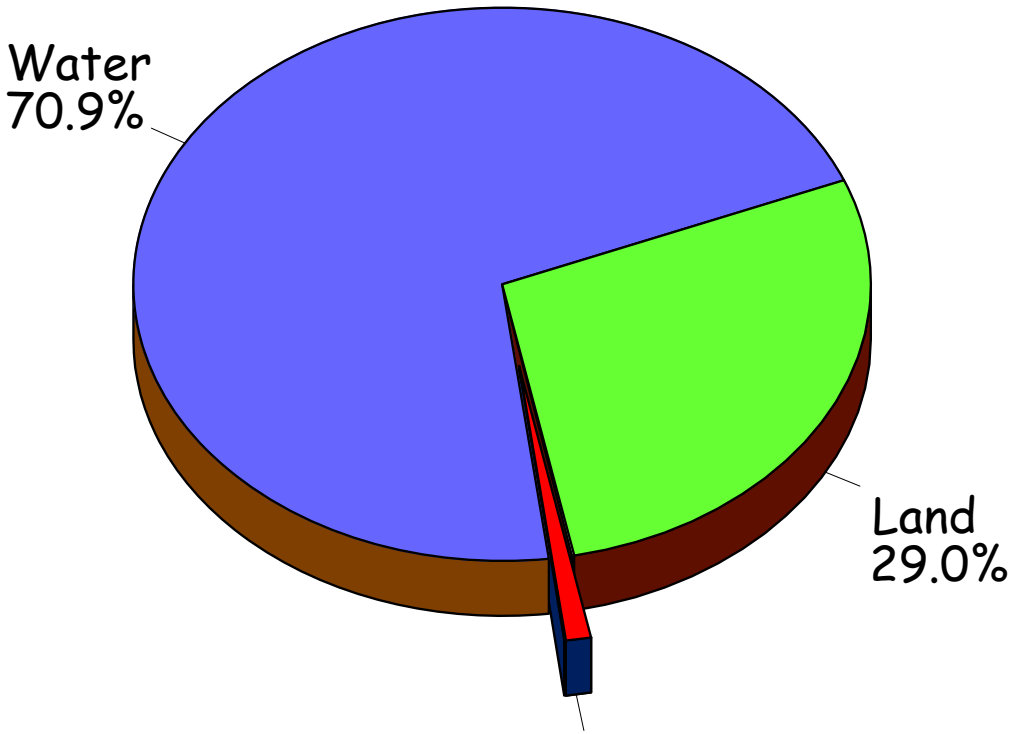
Total shipped 1982-98 = 3 km^2

Turner, Science 285,687 & Nate Lewis, Caltech

Combustion of biomass provides carbon neutral energy

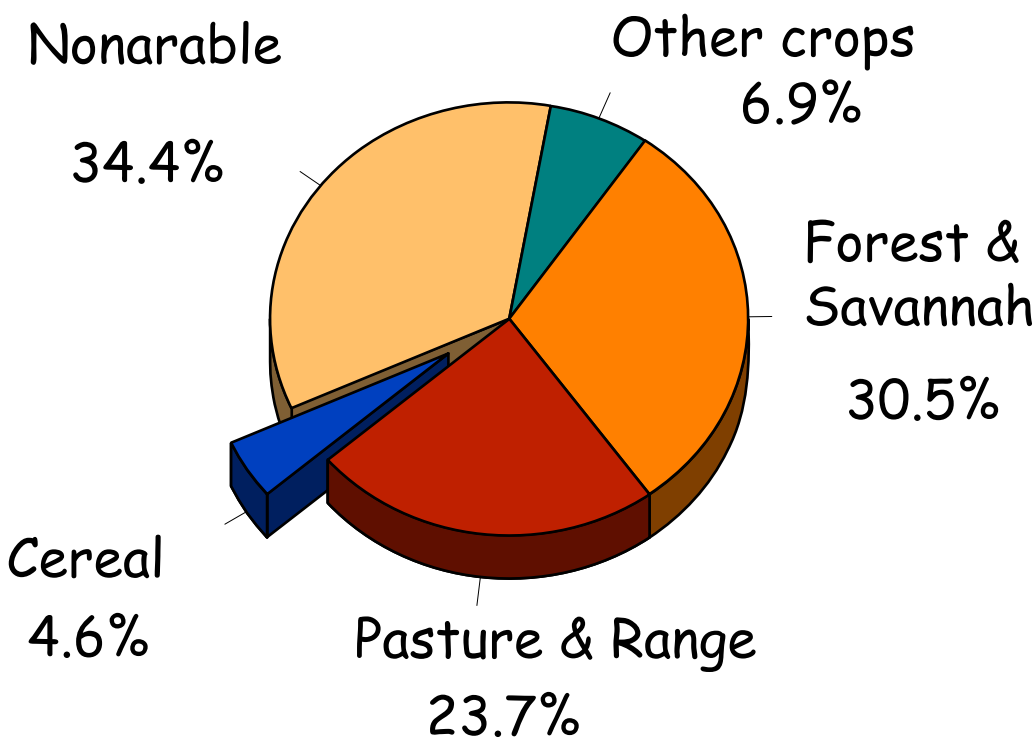


90,000 TW of energy arrives on the earths surface from the sun



Amount of land needed for 13 TW at 1% efficiency
5% of land
650 MHa

Land Usage

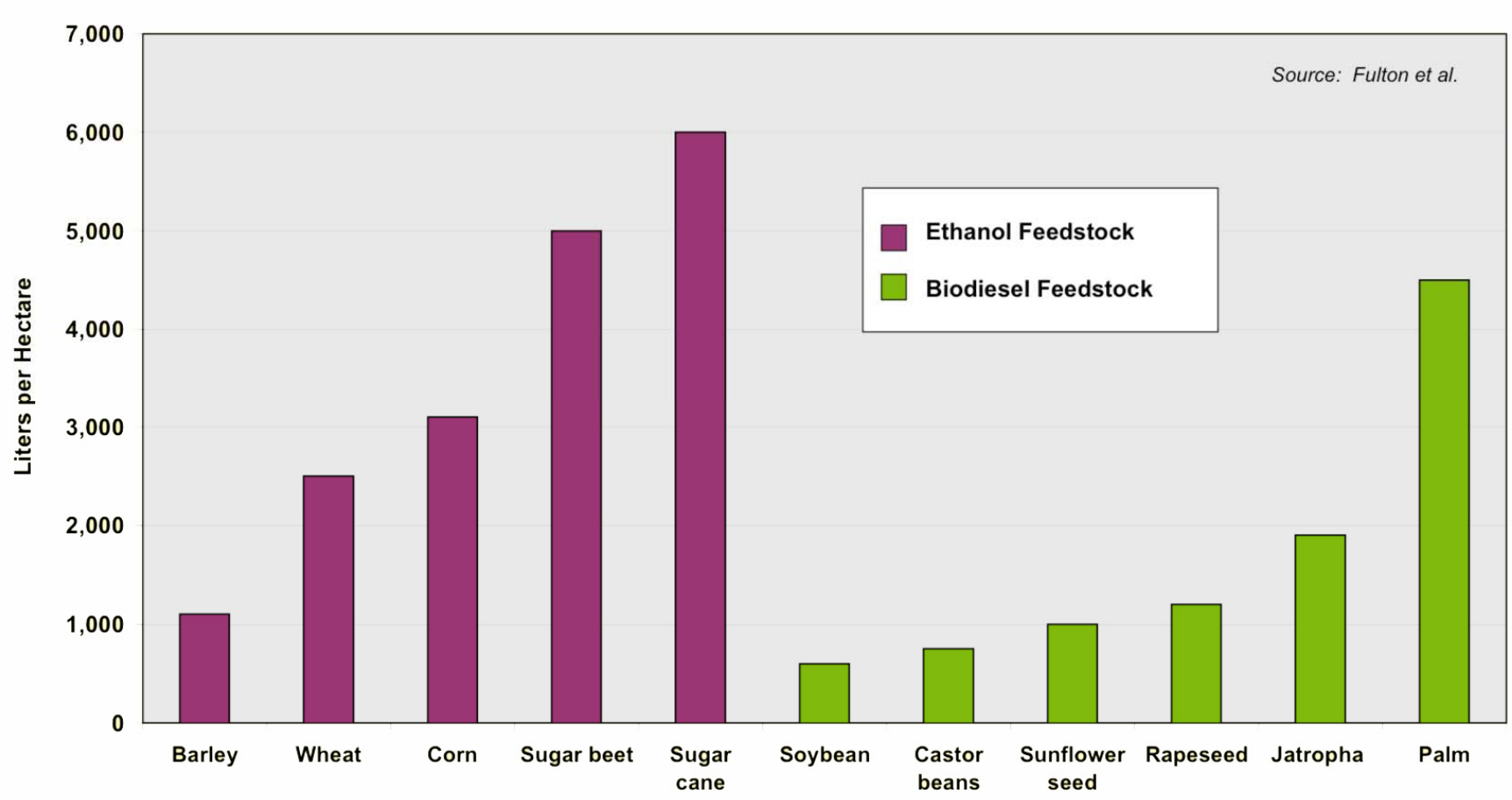


AMBIO 23,198 (Total Land surface 13,000 M Ha)

Types of biofuels

- Solid, burned directly
- Diesel
- Sugar to ethanol
- Cellulose to ethanol

Biofuel yields of various feedstocks

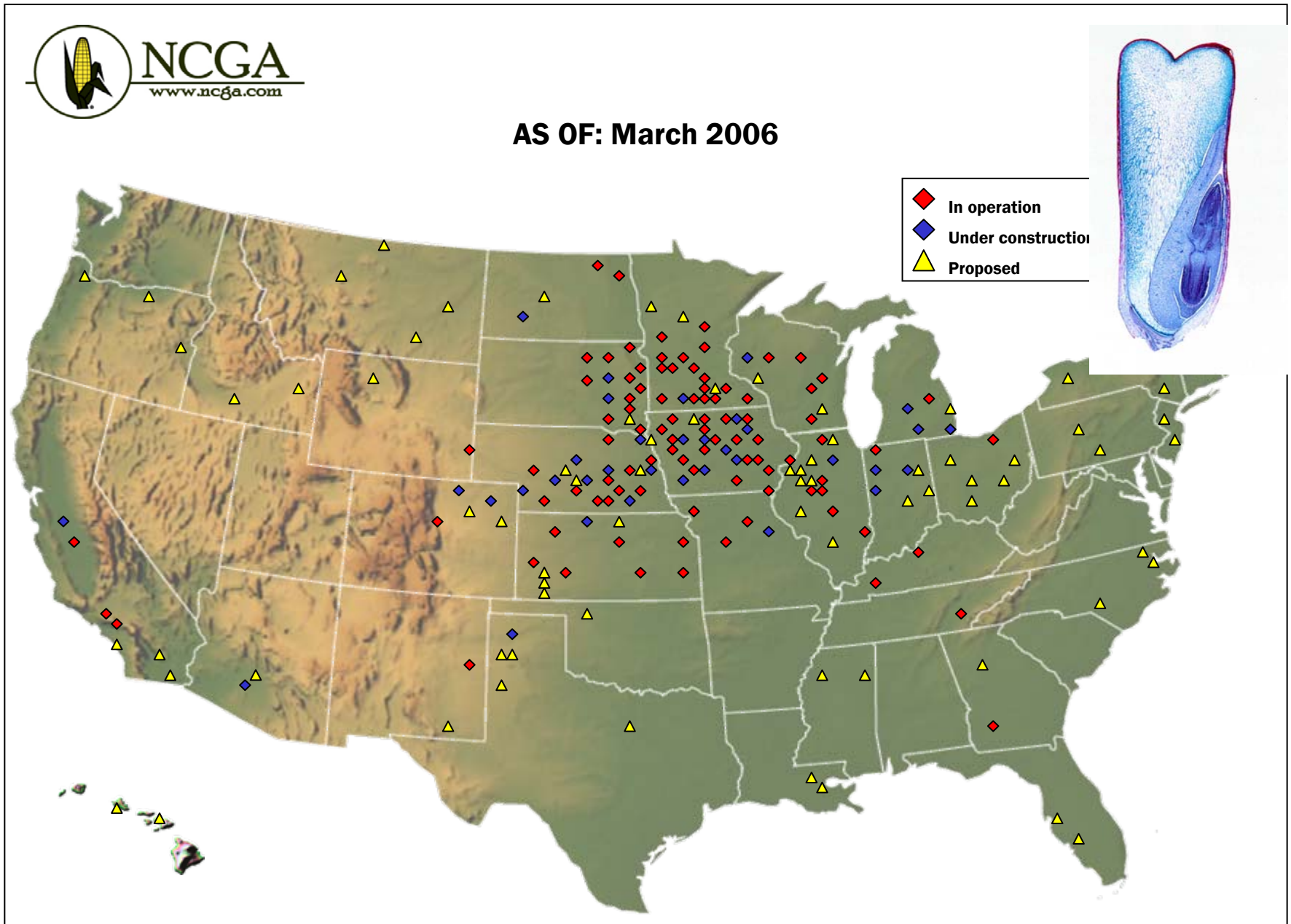


Worldwatch 2006

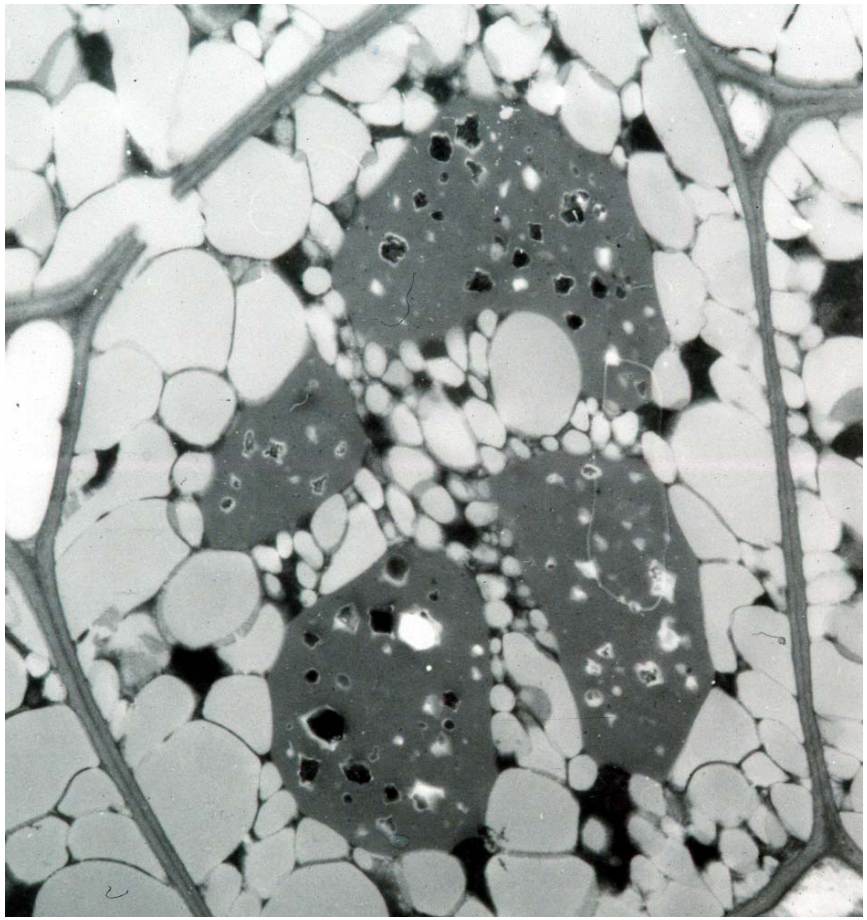
Overview of Brazil sugarcane

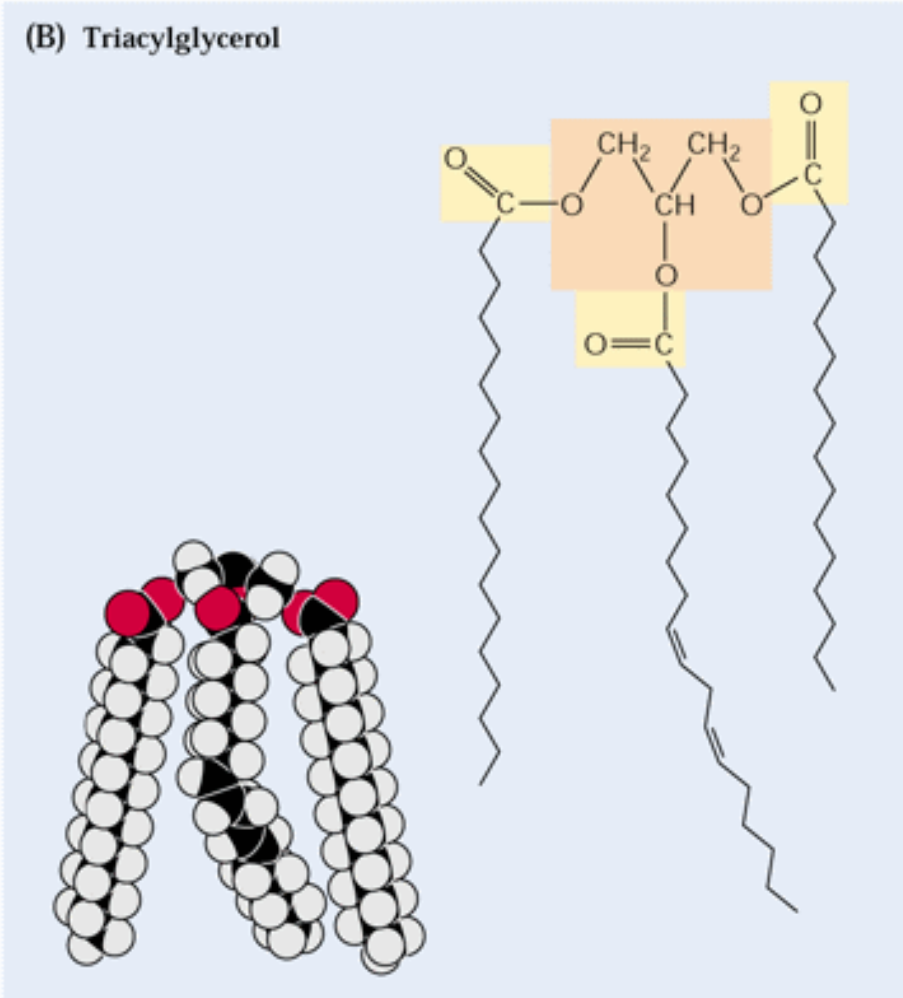
- 2007-08 harvest 528 MMT
- ~8 M Ha planted by 2008
- ~20 B liters ethanol, 2007
- ~80-120 T/Ha
- ~6400 L ethanol/Ha
- ~333 mills, 200 planned
- Plantings last 5 y, cut one per year
- Large mill
  - 22,000 tons/day
  - 1500 truck loads/day

US Biofuel Production has Expanded Rapidly

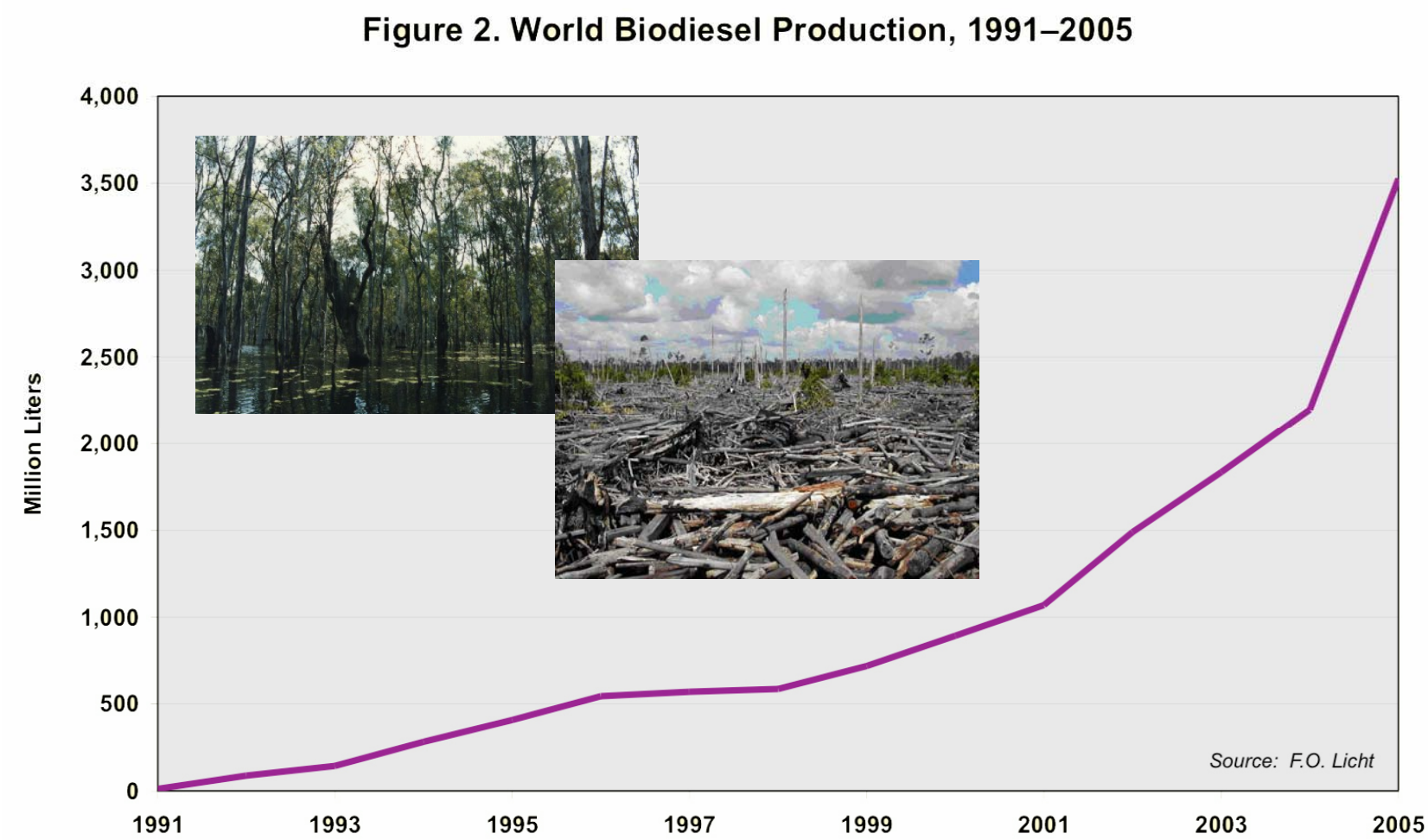


Some plants accumulate oil





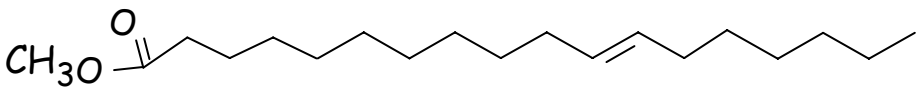
Biodiesel has been expanding rapidly



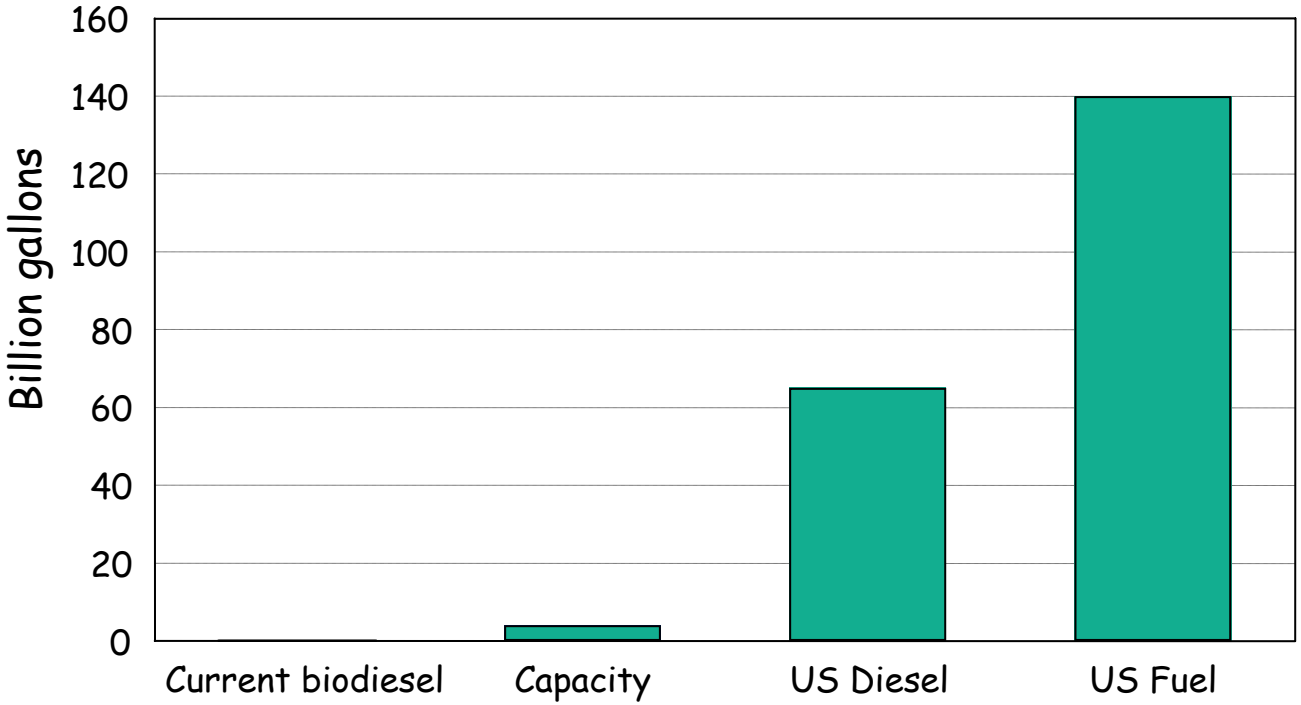
Worldwatch 2006 & Louise Fresco

Limited potential of biodiesel

(data from congressional research office)



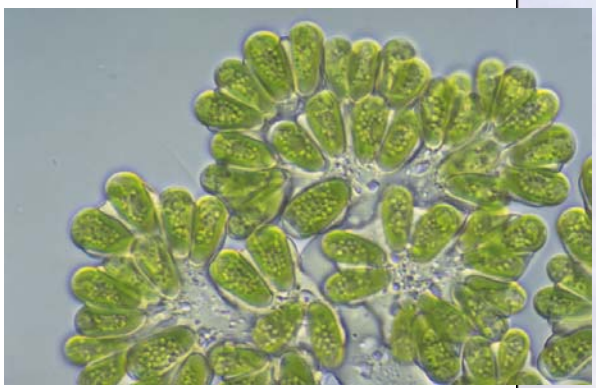
Biodiesel



65 biodiesel companies in operation, 50 in construction 2006

Use of algae could enable saline cultivation

Greenfuel bioreactor



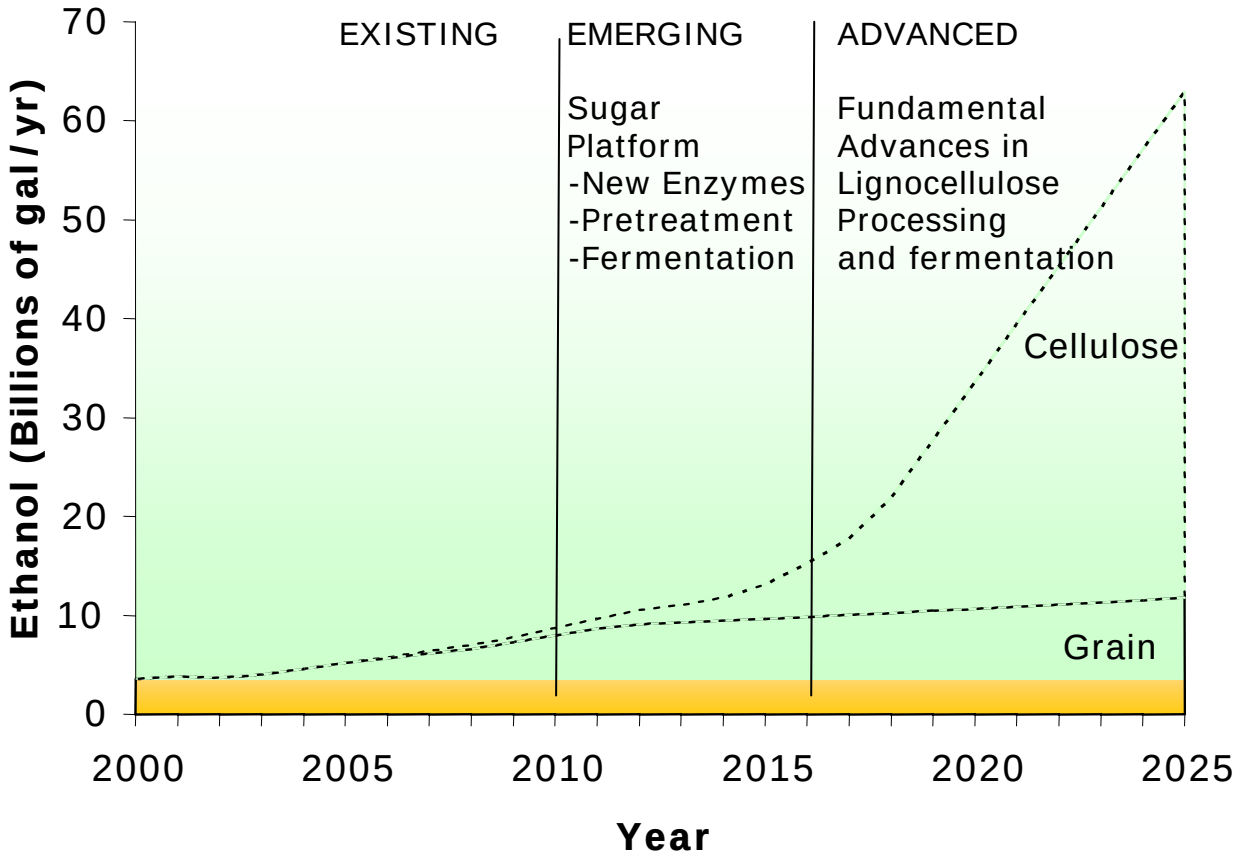
http://news.com.com/Photos+Betting+big+on+biodiesel/2009-1043_3-5714336.html?tag=st.prev

How Much Ethanol Could the Municipal Solid Waste from a City With 1 Million People Produce?

The average person in the United States generates approximately 1.8 kilograms of municipal solid waste (MSW) every day. Of this, typically about 75 percent is predominantly cellulosic organic material, including waste paper, wood wastes, cardboard, and waste food scraps. Thus, a city with 1 million people produces around 1,800 tonnes of MSW in total, or about 1,300 tonnes per day of organic material. Using technology that could convert organic waste to ethanol, roughly 330 liters of ethanol could be produced per tonne of organic waste. Thus, organic waste from a city with 1 million people would be enough feedstock to produce about 150 million liters per year. This is enough fuel to meet the needs of more than 58,000 people in the United States; 360,000 people in France; or nearly 2.6 million people in China at current rates of per capita fuel use.

Worldwatch, 2006

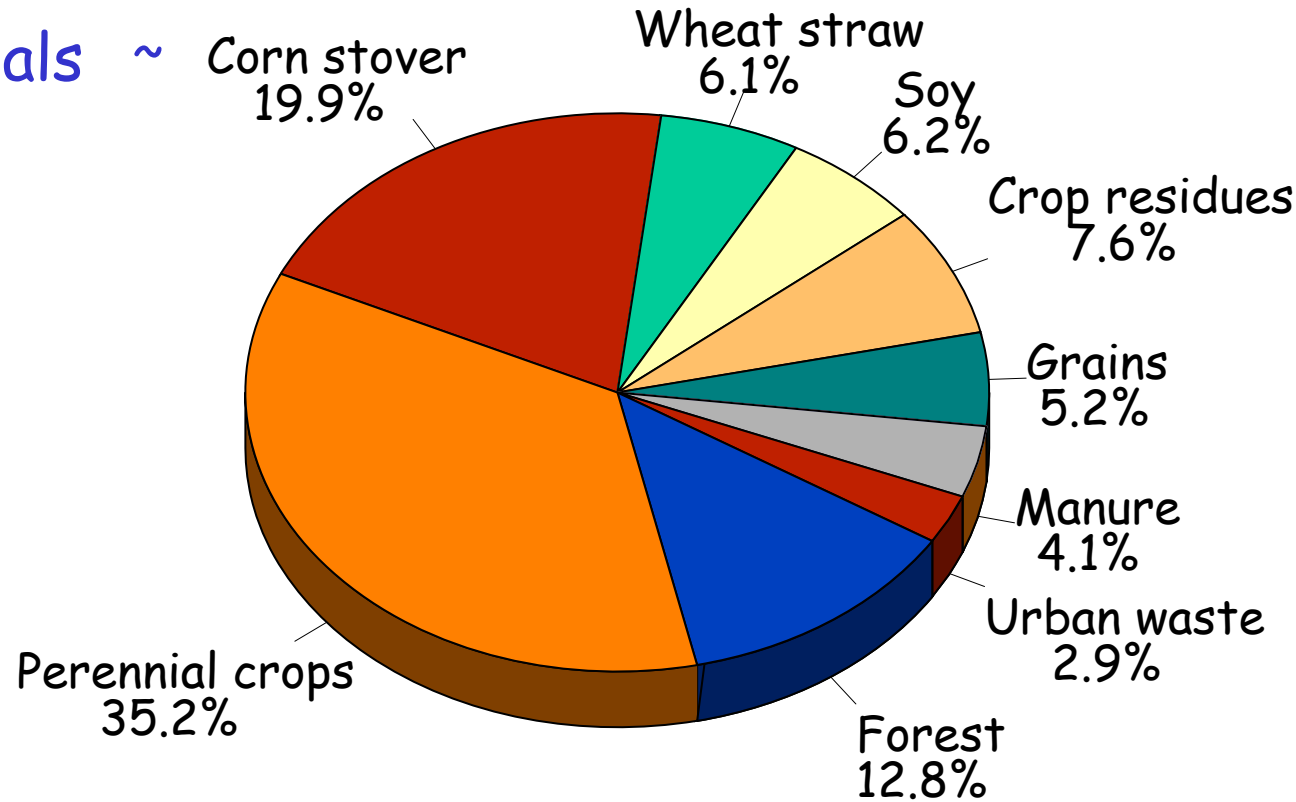
Cellulosic fuels are expected to become the dominant source of biofuels



Modified from Richard Bain, NREL

US Biomass inventory = 1.3 billion tons

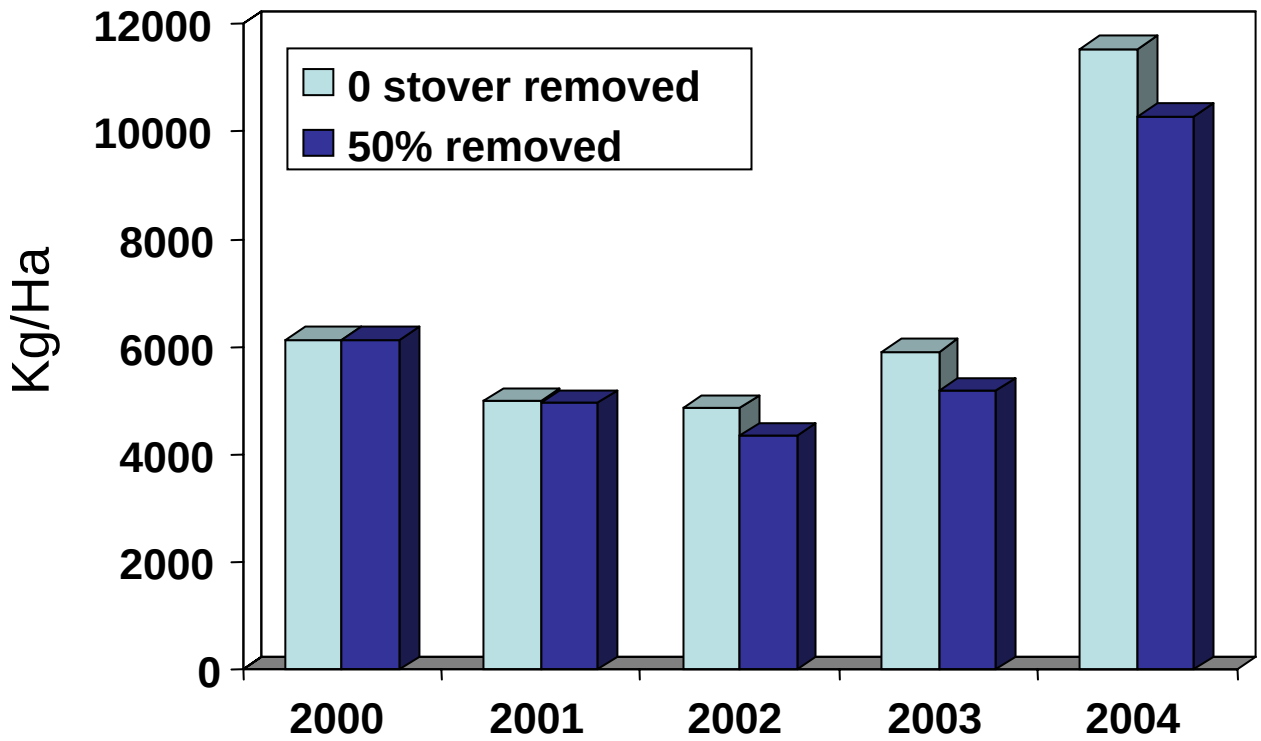
26 B gals ~



From: Billion ton Vision, DOE & USDA 2005

Effect of 50% stover removal on corn grain yields in eastern NE.

(120kg N/ha)



K. Vogel et al., unpublished

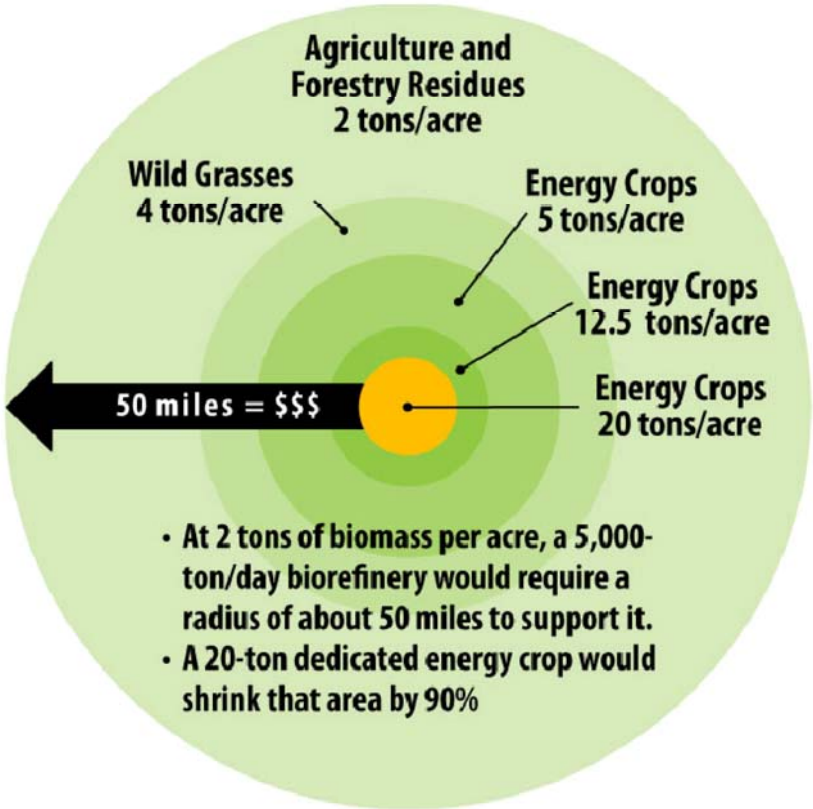
Potential bioenergy crops tested in the US

English name	Latin name	Photo- synthetic pathway	Yields reported [t DM ha^{-1} a^{-1}][a]
Crested wheatgrass	*Agropyron desertorum* (Fisch ex Link) Schult.	C_3	16.3
Redtop	*Agrostis gigantea* Roth	C_3	Not available
Big bluestem	*Andropogon gerardii* Vitman	C_4	6.8–11.9
Smooth bromegrass	*Bromus inermis* Leyss.	C_3	3.3–6.7
Bermudagrass	*Cynodon dactylon* L.	C_4	1.0–1.9
Intermediate wheatgrass	*Elytrigia intermedia* [Host] Nevski	C_3	Not available
Tall wheatgrass	*Elytrigia pontica* [Podp.] Holub	C_3	Not available
Weeping lovegrass	*Eragrostis curvula* (Schrad.) Nees	C_4	6.8–13.7
Tall Fescue	*Festuca arundinacea* Schreb.	C_3	3.6–11.0
Switchgrass	*Panicum virgatum* L.	C_4	0.9–34.6
Western wheatgrass	*Pascopyrum smithii* (Rydb.) A. Love	C_3	Not available
Bahiagrass	*Paspalum notatum* Flugge	C_4	Not available
Napiergrass (elephant grass)	*Pennisetum purpureum* Schum	C_4	22.0–31.0
Reed canary grass	*Phalaris arundinacea* L.	C_3	1.6–12.2
Timothy	*Phleum pratense* L.	C_3	1.6-6.0
Energy cane	*Saccharum* spp.	C_4	32.5
Johnsongrass	*Sorghum halepense* (L.) Pers.	C_4	14.0–17.0
Eastern gammagrass	*Tripsacum dactyloides* (L.) L.	C_4	3.1–8.0

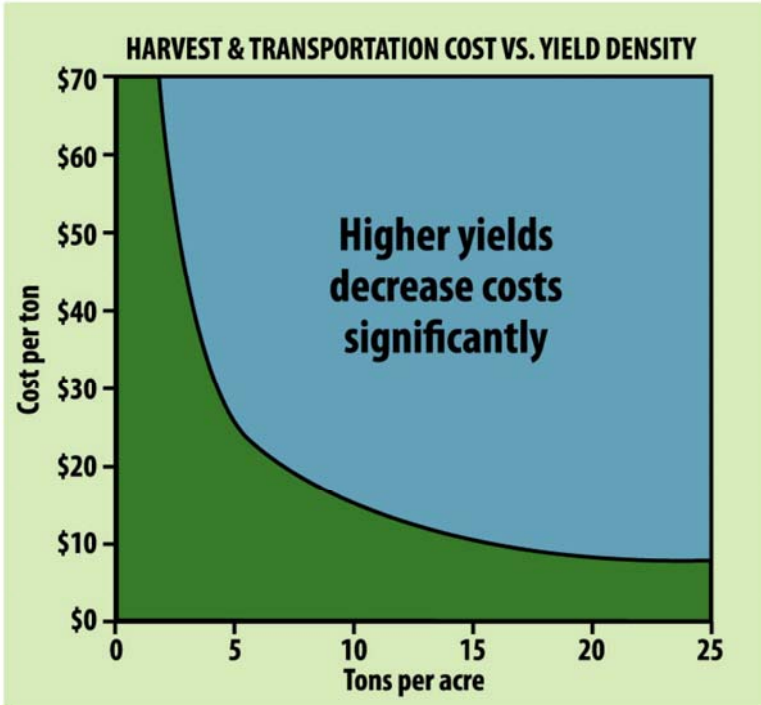
[a] t = Mg.

From Lewandowski et al., Biomass & Bioenergy 25,335

High yield decreases transportation and land costs



500,000 gal/day scenario



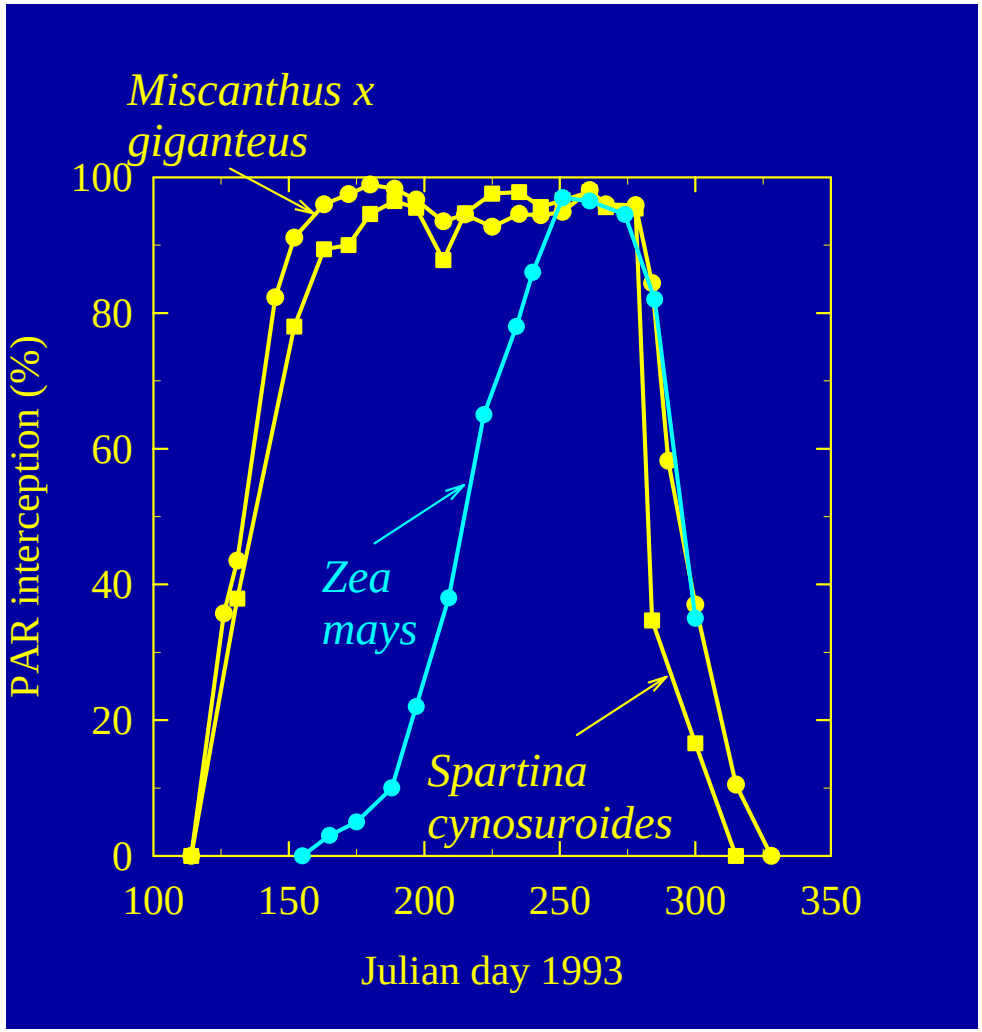
Richard Hamilton, Ceres

>2% yield is feasible

Yield of 26.5 tons/acre observed by Young & colleagues in Illinois, without irrigation

Courtesy of Steve Long et al

Perennials have more photosynthesis



Courtesy of Steve Long, University of Illinois

Locations of European Miscanthus Trials

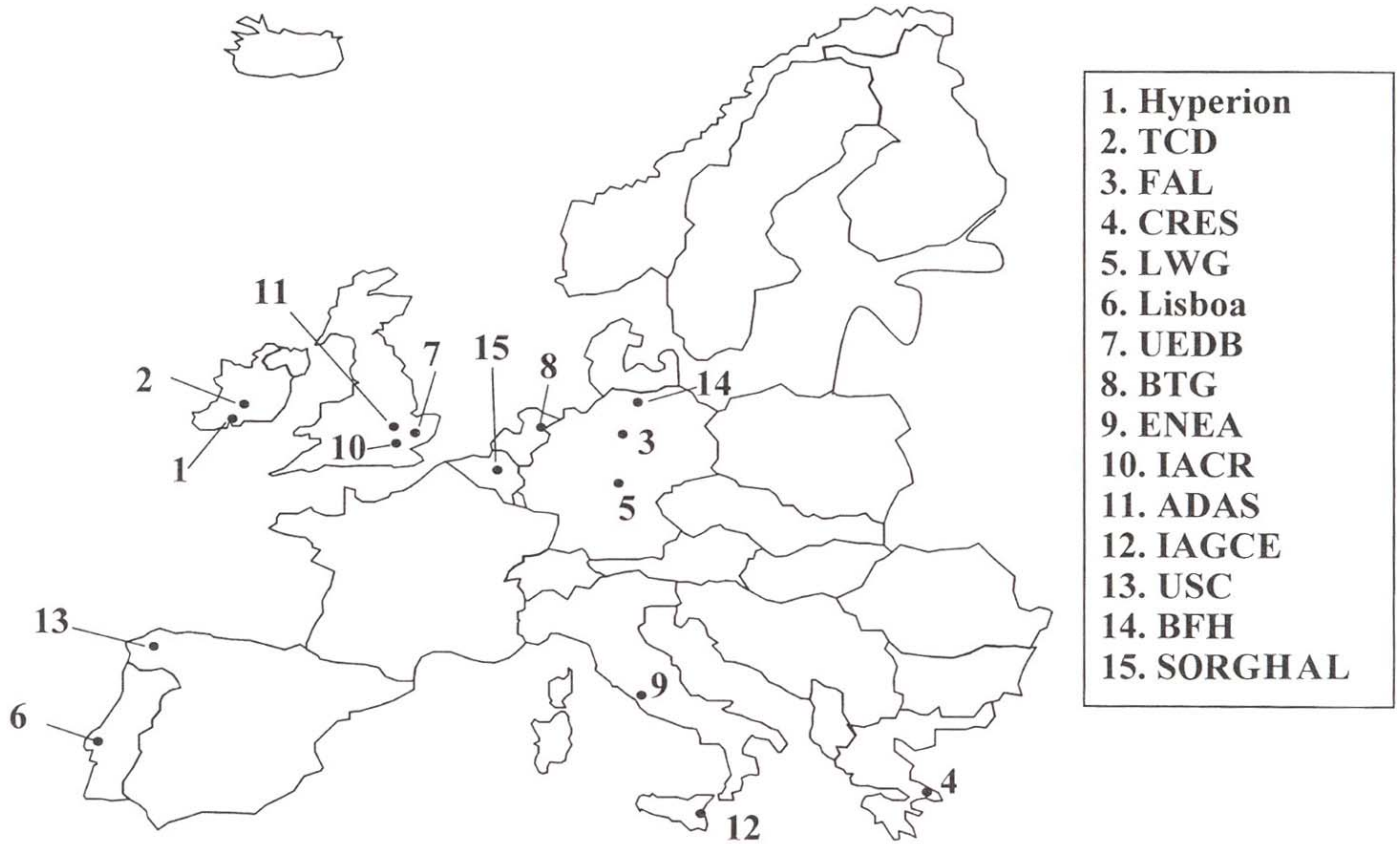
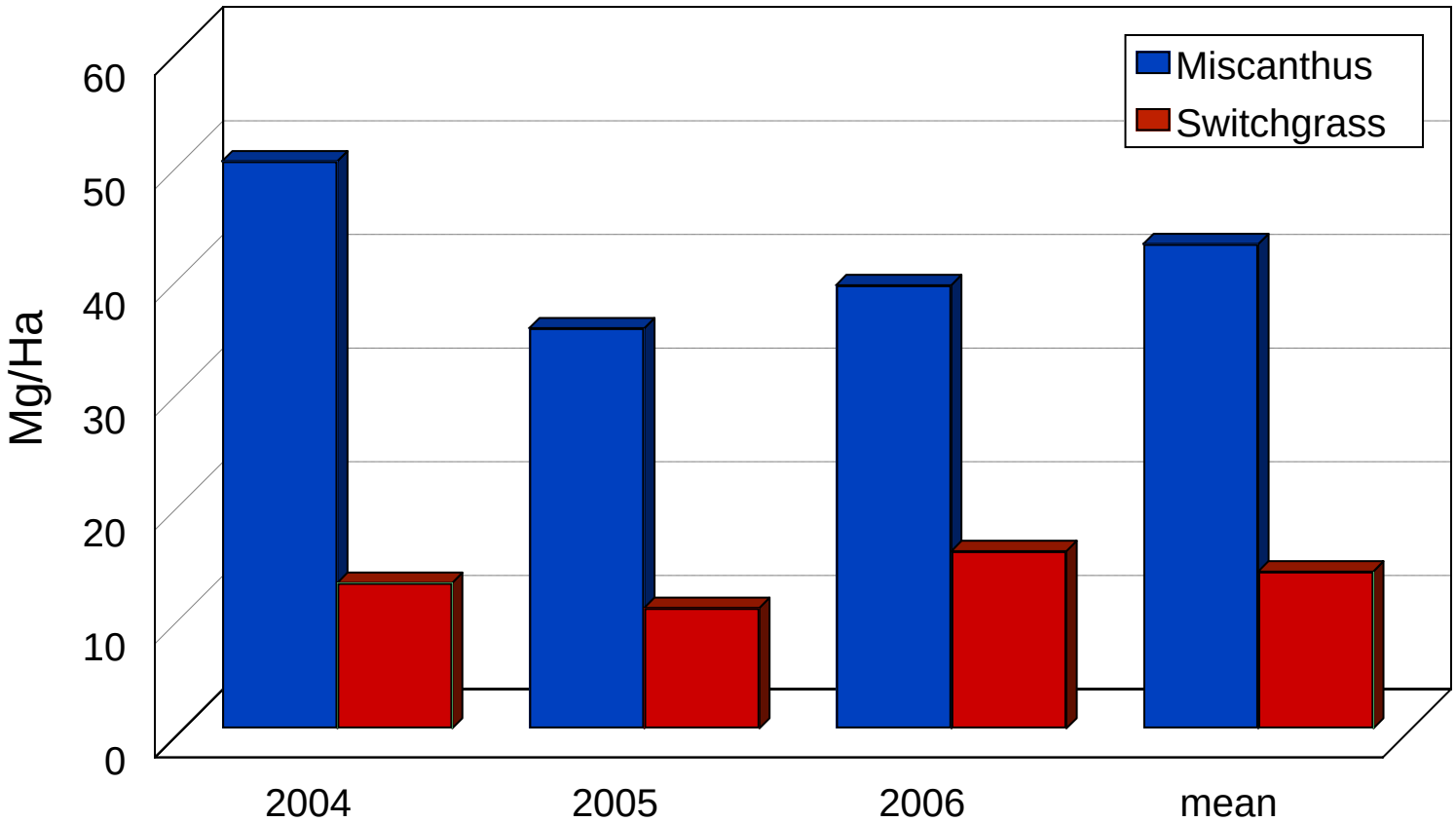


Figure 4.6. Geographical distribution of the trials in the European Miscanthus *Productivity Network. See Preface for key to acronyms*

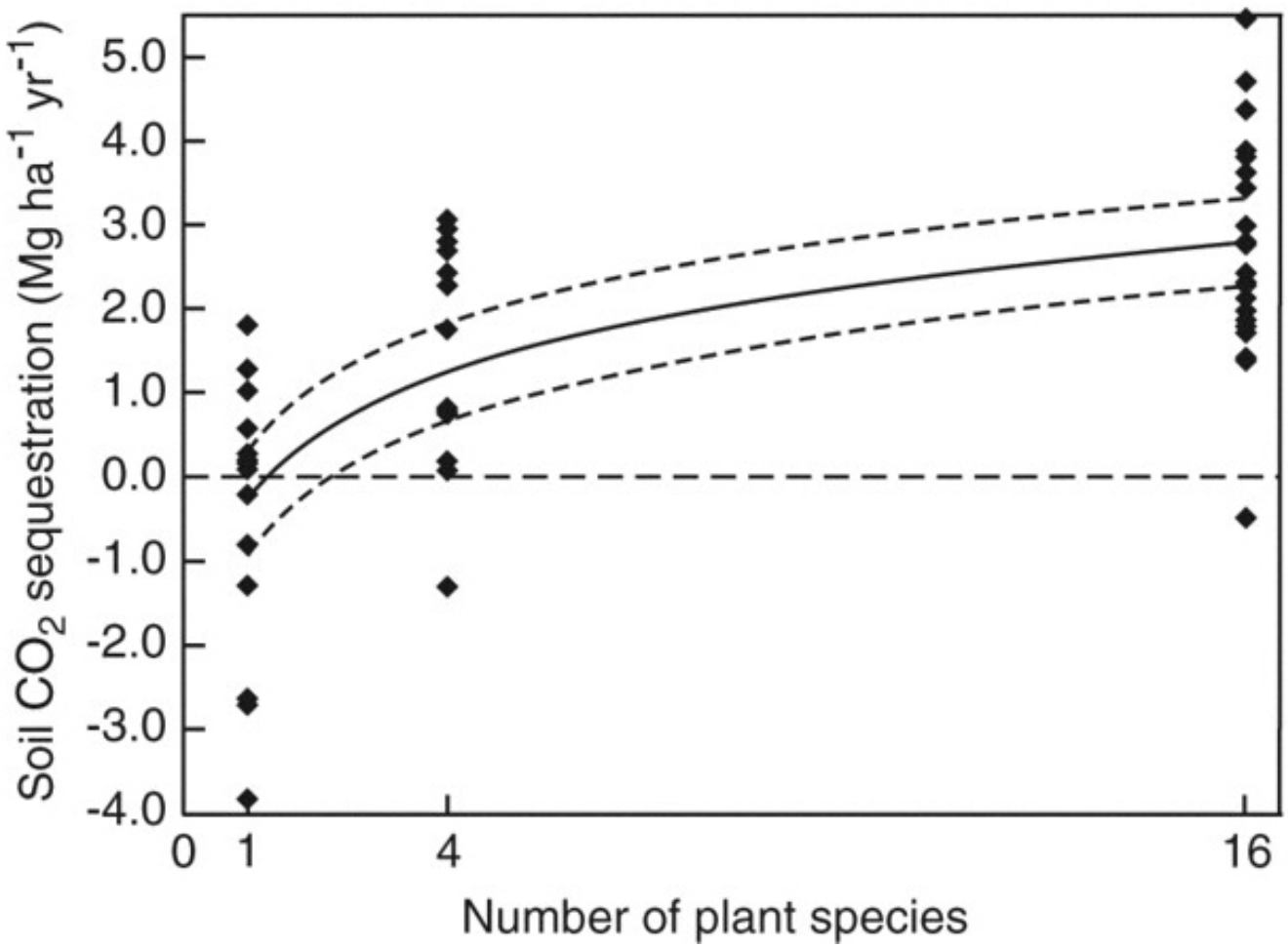
From: Clifton-Brown et al in: Jones and Walsh (eds) Miscanthus for Energy and Fibre, 2001

Yield comparison of two energy crops



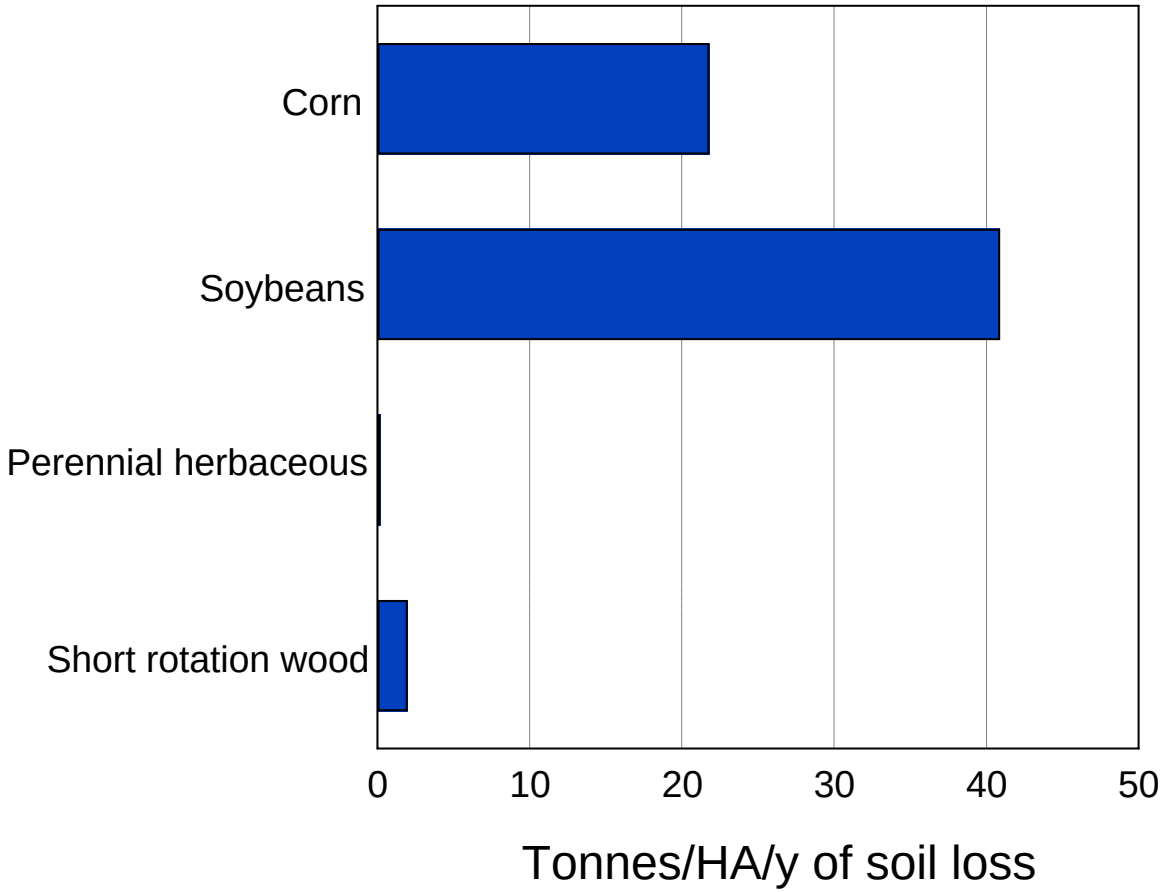
Heaton and Long, submitted

Soil carbon increases in perennial crops with all aboveground biomass removed



Tilman, Hill & Lehman Science 314,1598

Perennials have little or no erosion

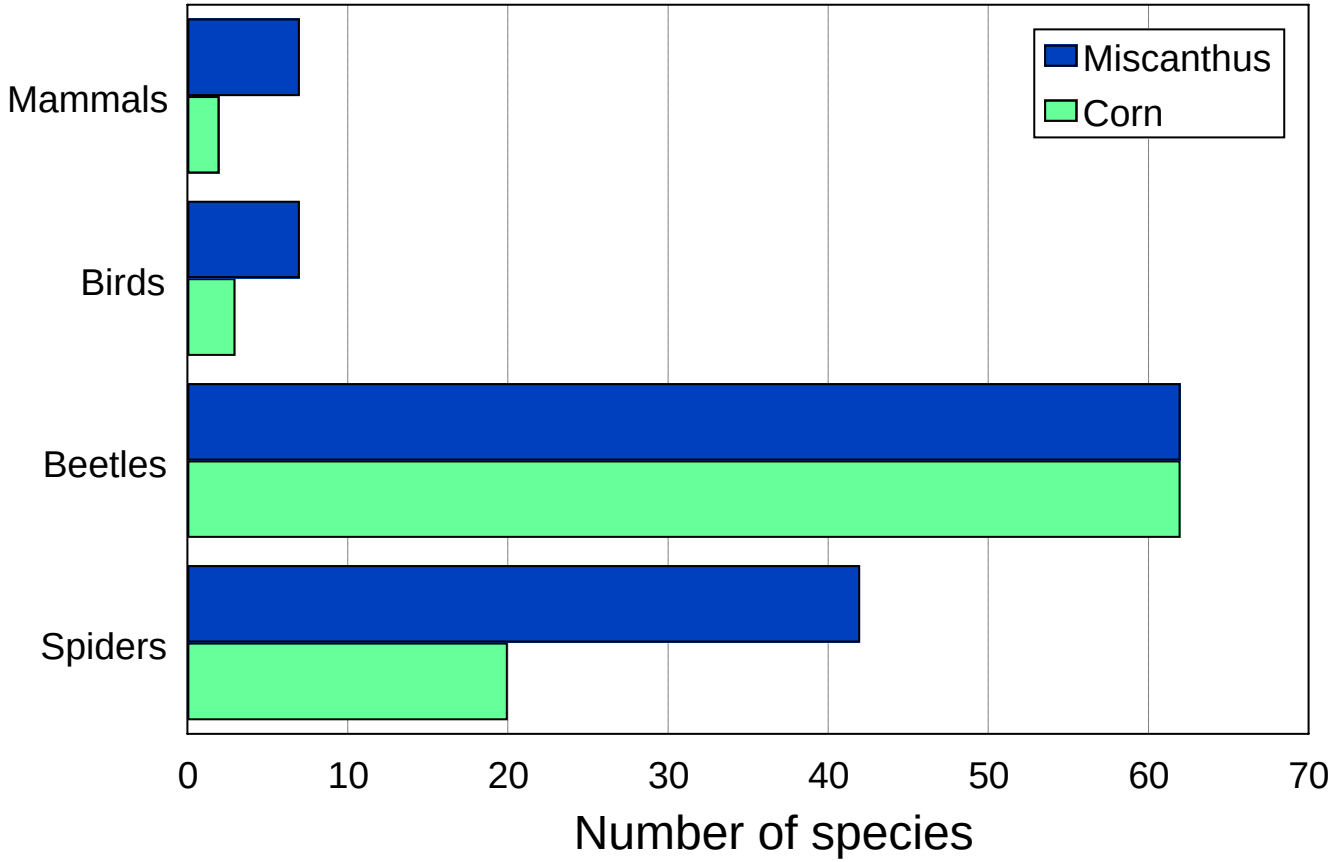


From Oliveira et al in: Jones and Walsh (eds) Miscanthus for Energy and Fibre, 2001

Harvesting Miscanthus

http://bioenergy.ornl.gov/gallery/index.html

Ecological niches in Miscanthus vs corn in Germany

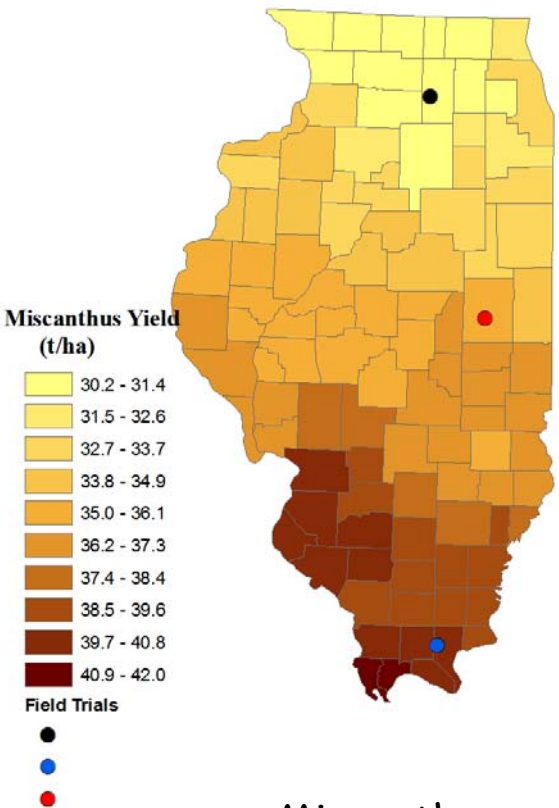


From Oliveira et al in: Jones and Walsh (eds) Miscanthus for Energy and Fibre, 2001

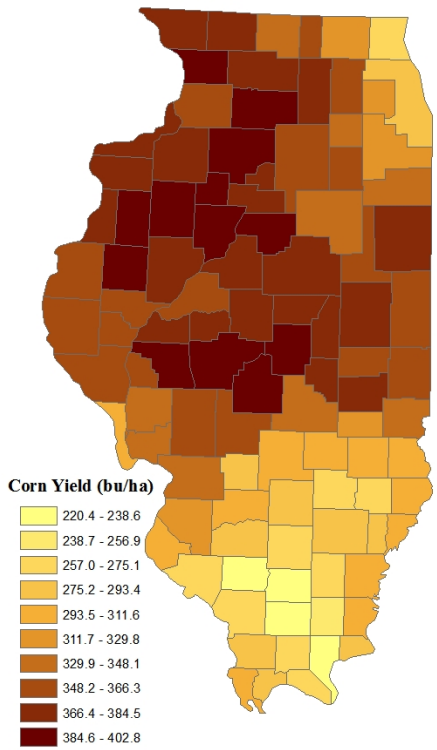
More extensive analysis in Semere & Slater (2007) Biomass & Energy 31,30

Energy crops may not compete directly with food crops

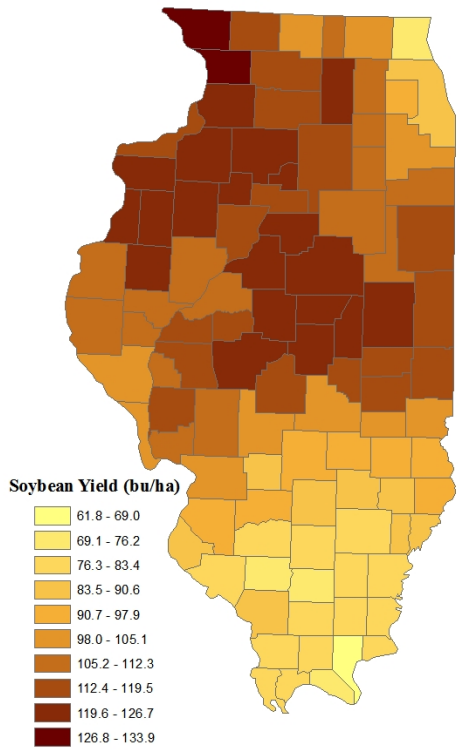
(yield per HA for Miscanthus, Corn, Soybean)



Miscanthus



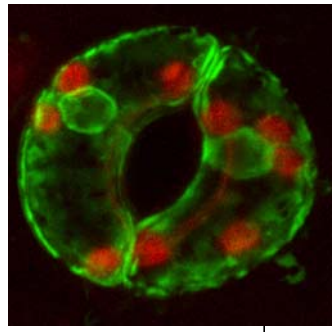
Corn

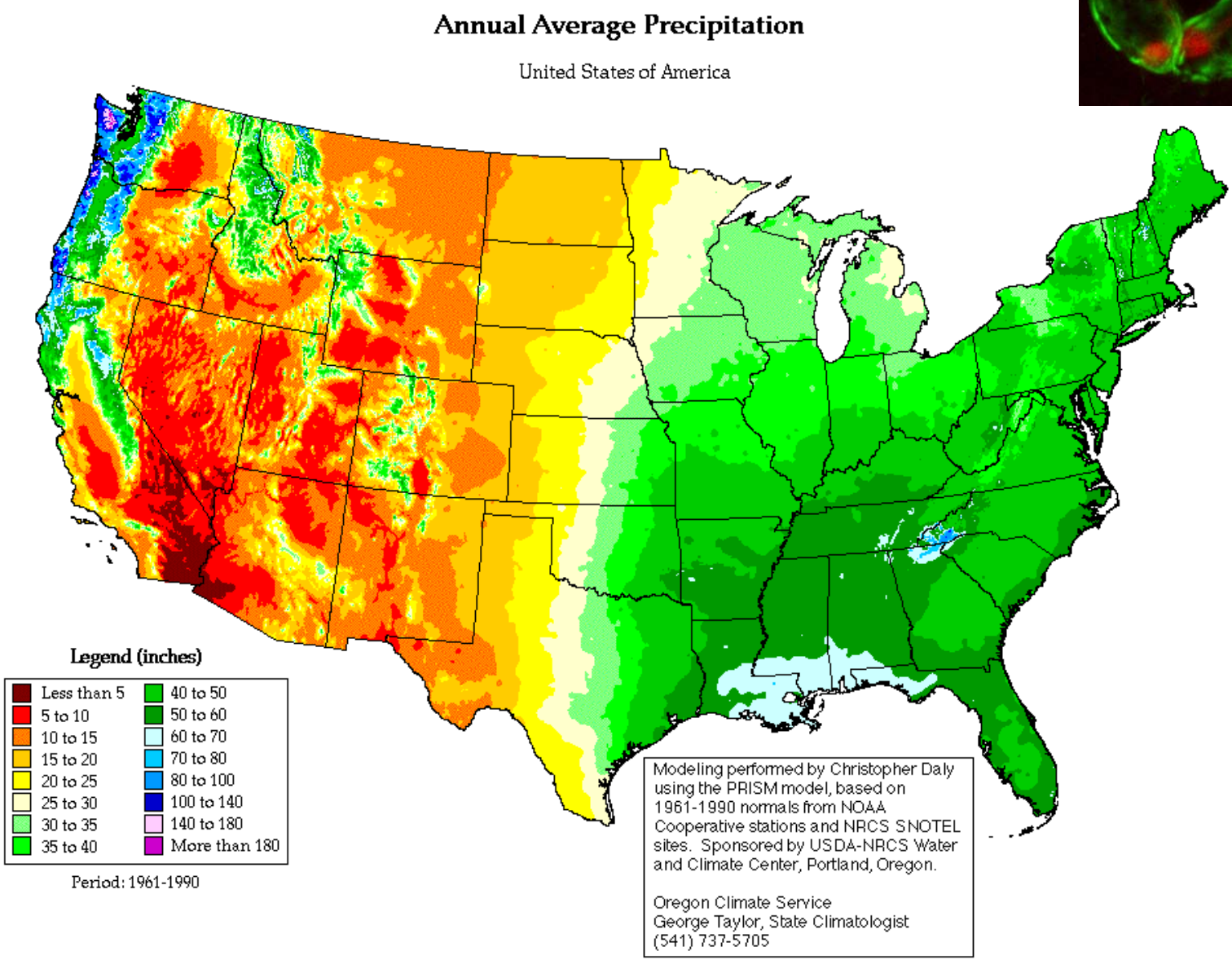


Soybean

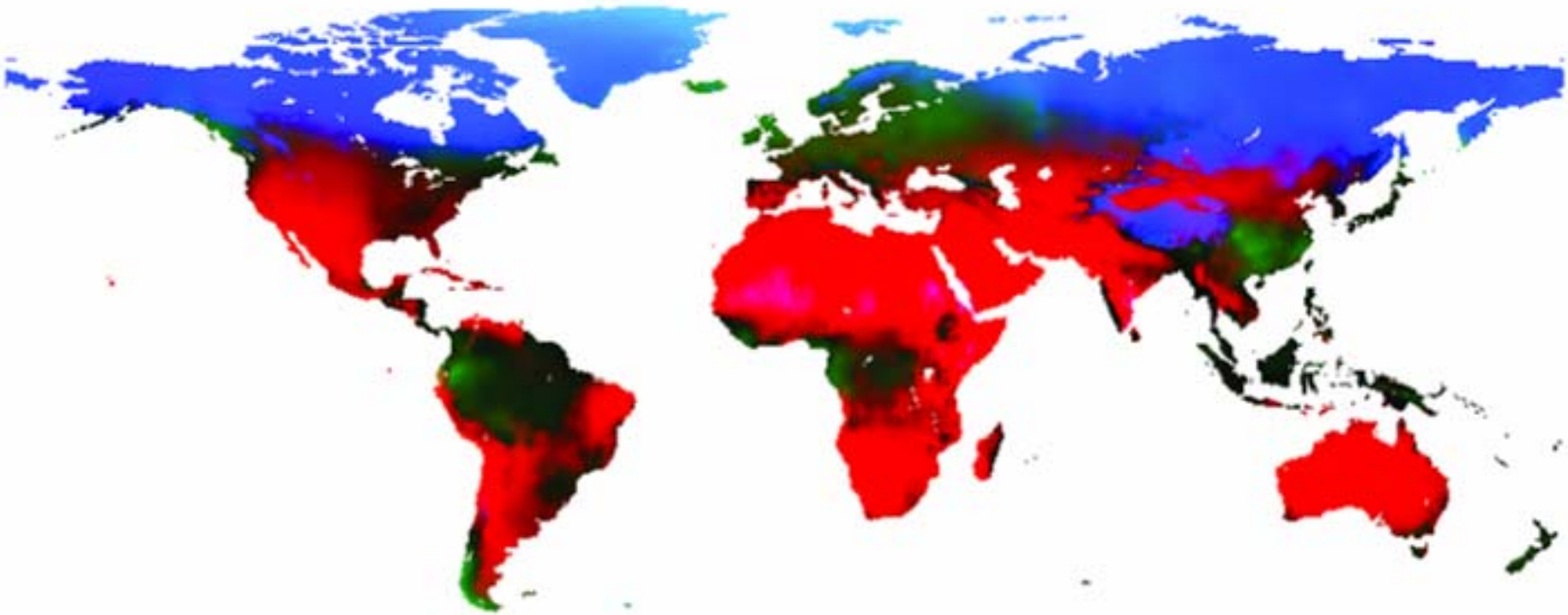
Madhu Khanna, University of Illinois, Urbana

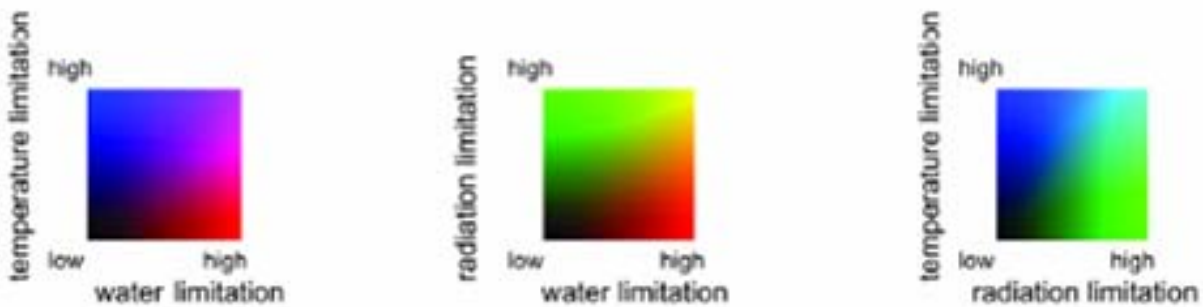
Annual precipitation





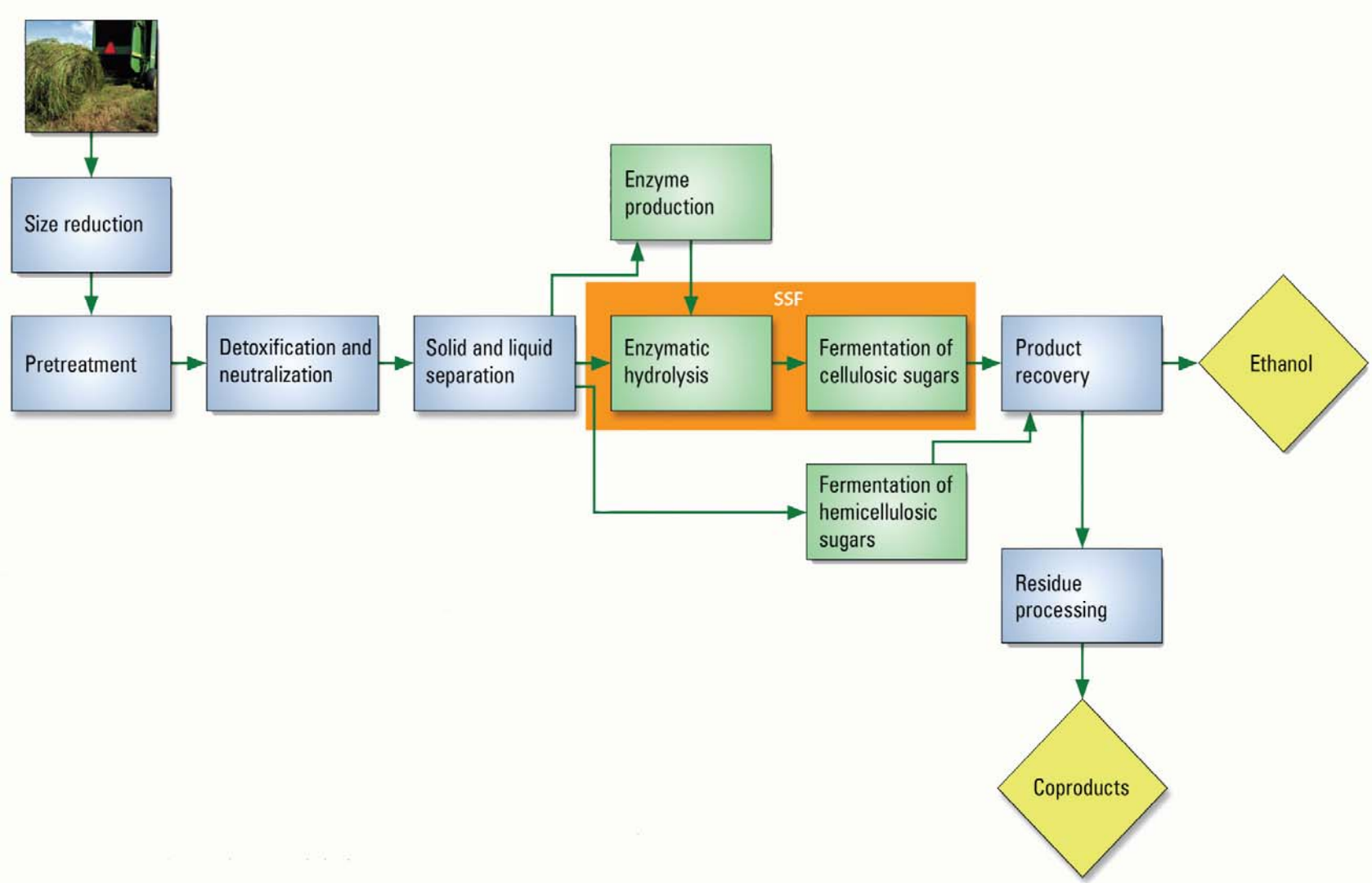
Limiting factors for global NPP





Baldocchi et al. 2004 SCOPE 62

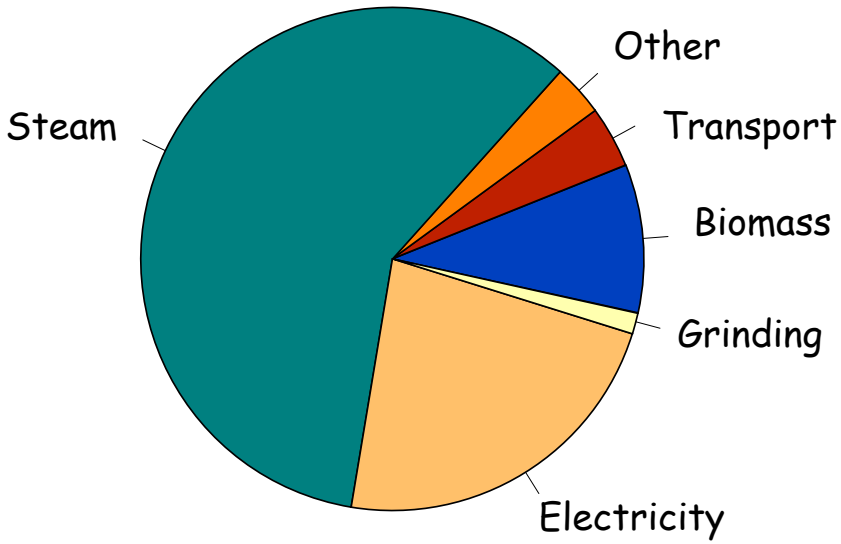
Steps in cellulosic ethanol production



From: Breaking the Biological Barriers to Cellulosic Ethanol

The challenge is efficient conversion

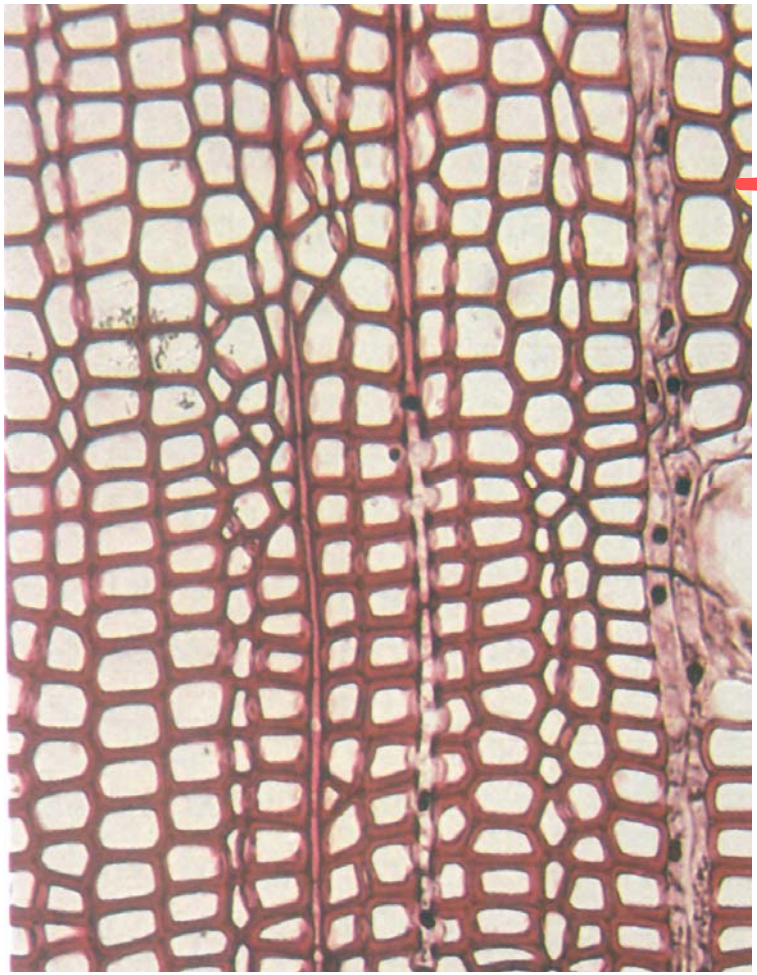
- Burning switchgrass (10 t/ha) yields 14.6-fold more energy than input to produce*
- But, converting switchgrass to ethanol calculated to consume 45% more energy than produced



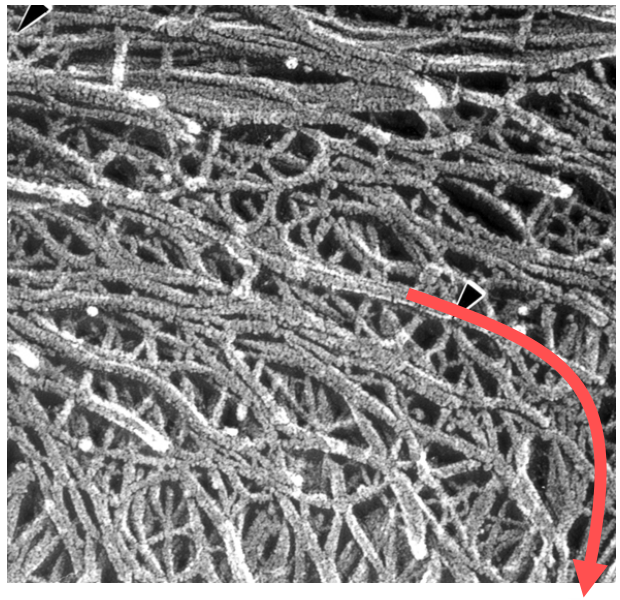
Energy consumption

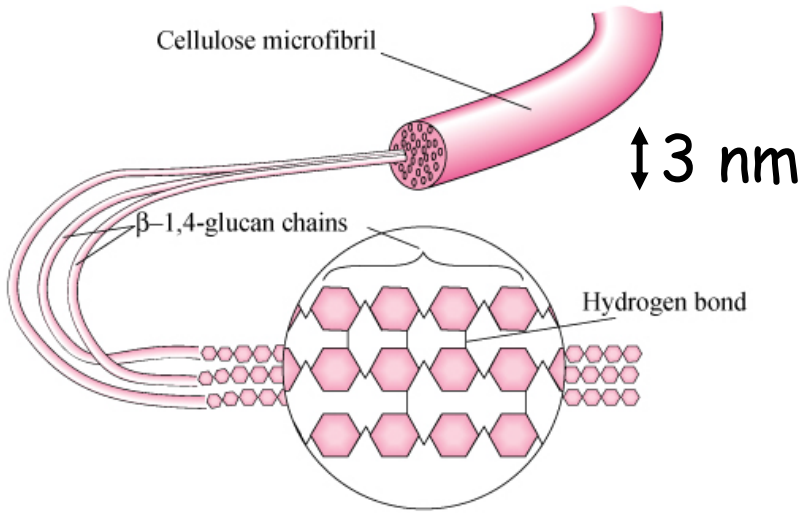
*Pimentel & Patzek, Nat Res Res 14,65 (2005)

Plants are mostly composed of sugars



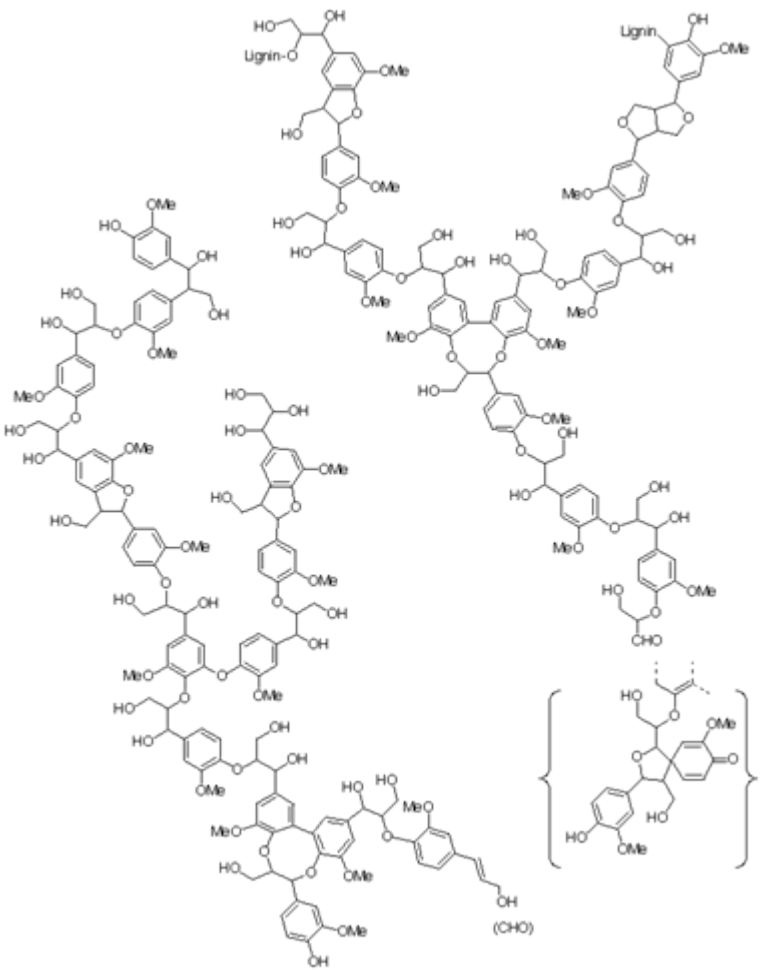
Section of a pine board

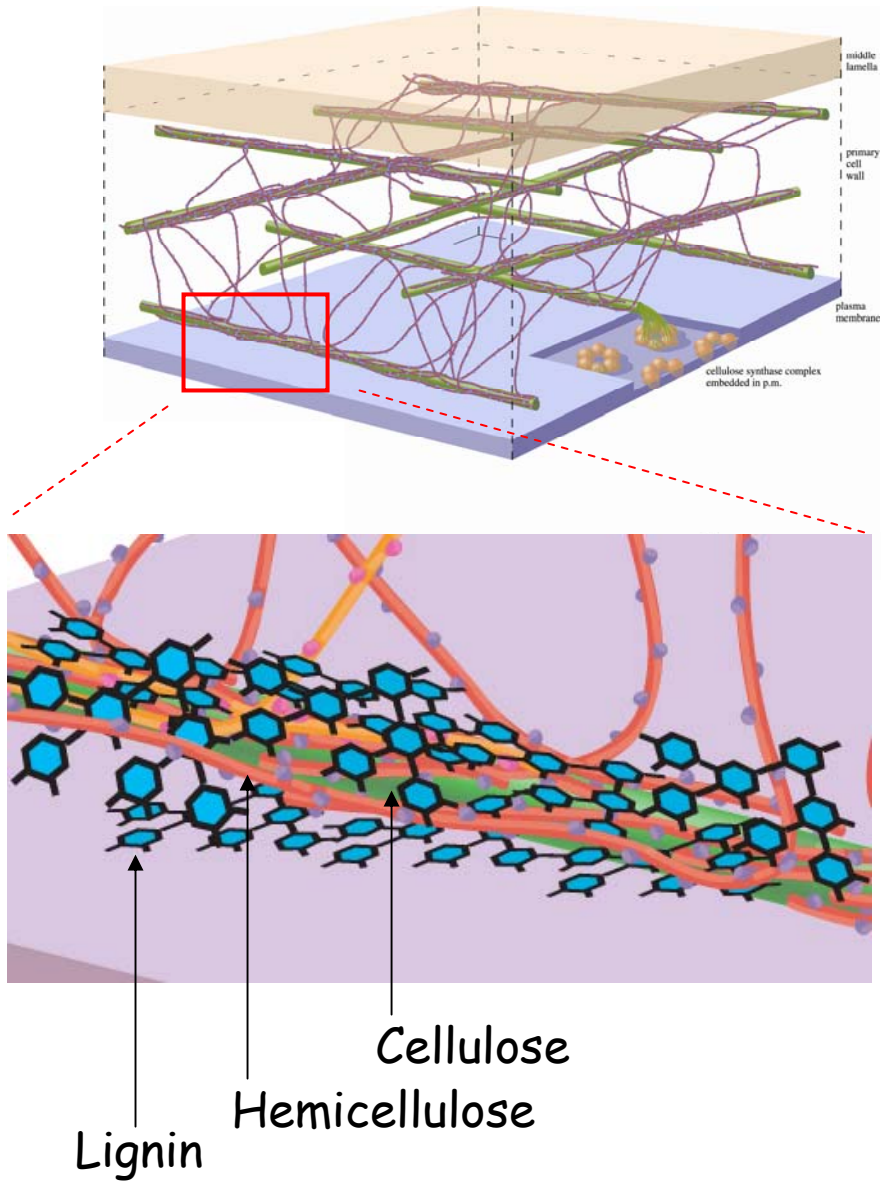




Polymerized glucose

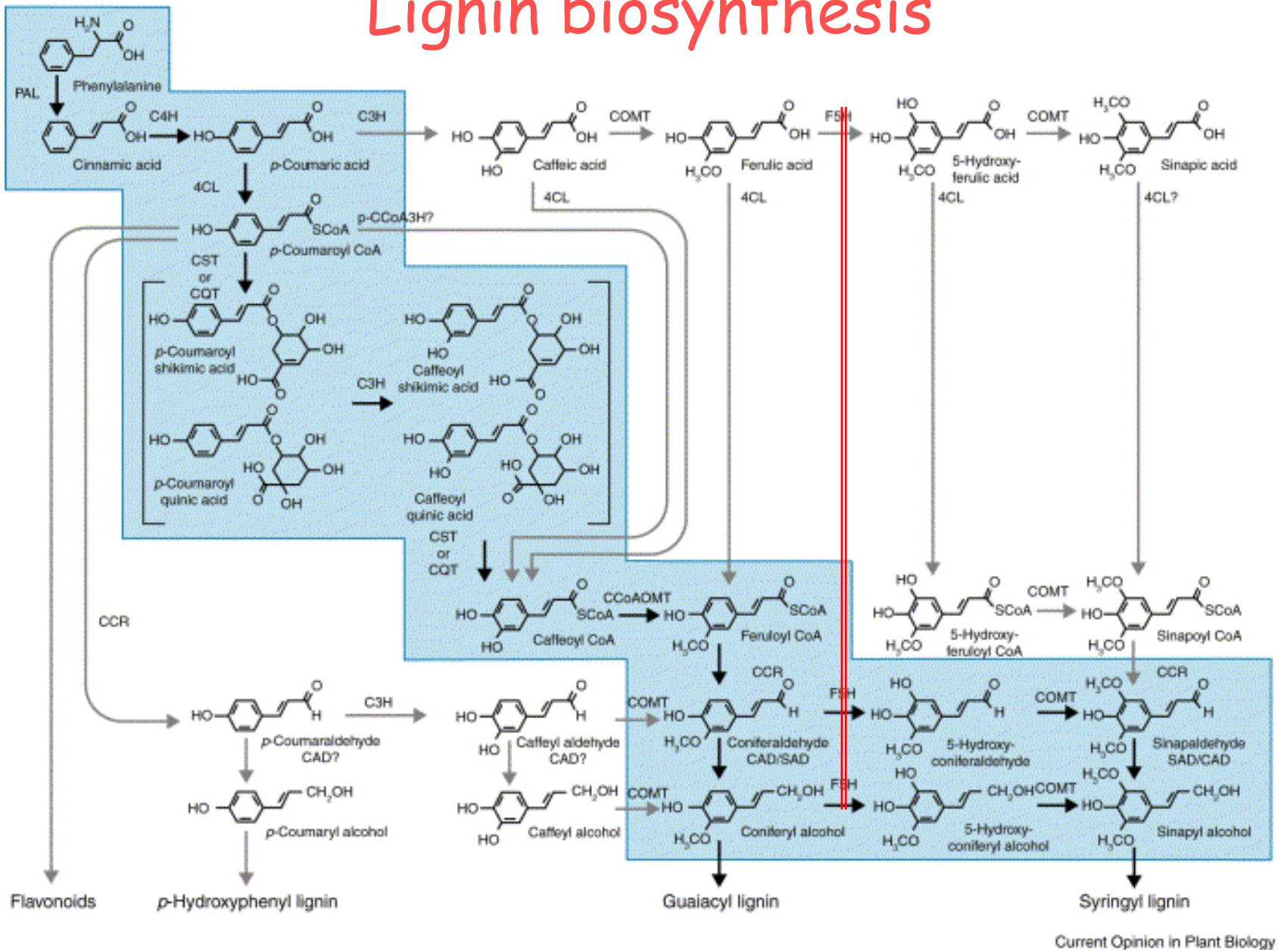
Lignin occludes polysaccharides





John Ralph, U Wisconsin

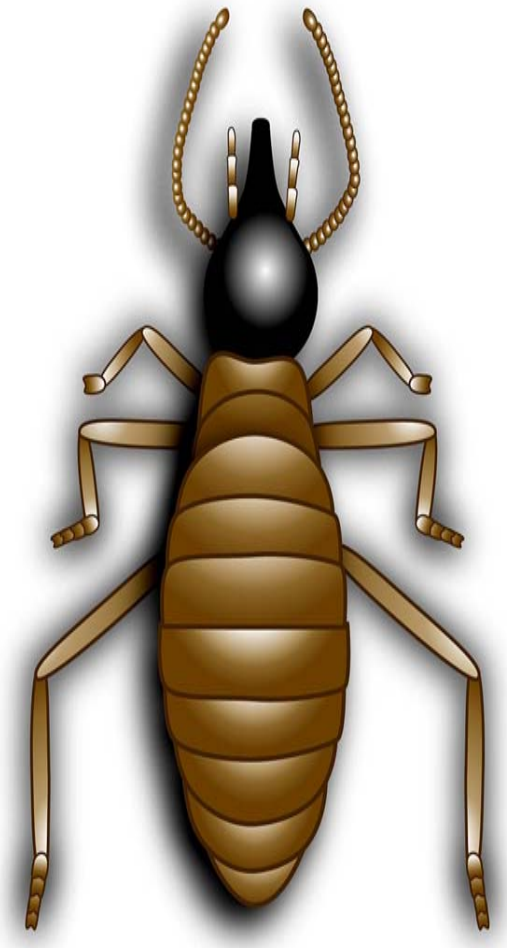
Lignin biosynthesis



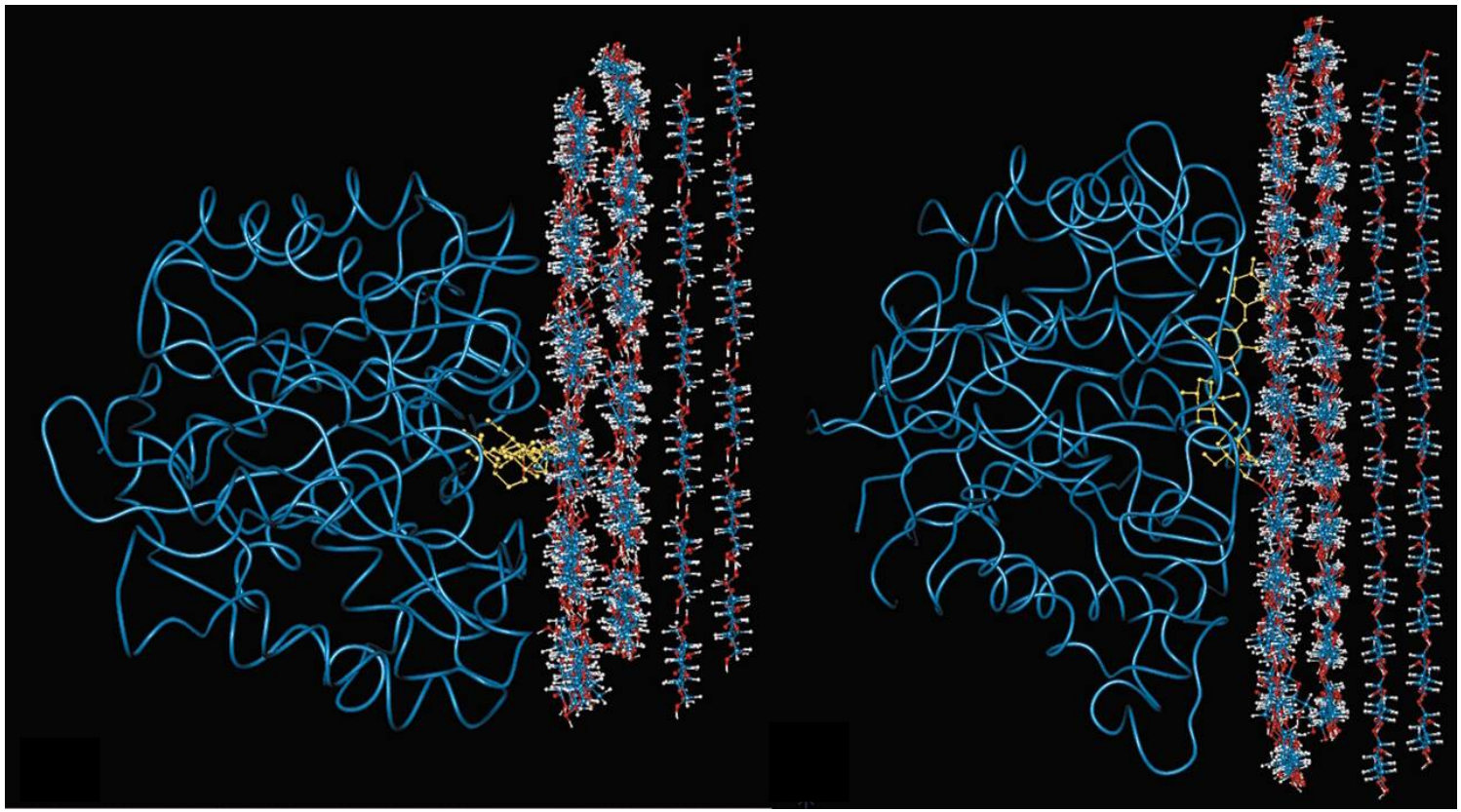
Humphreys and Chapple, Curr Opin Plant Biol 5,224

Possible routes to improved catalysts

- Explore the enzyme systems used by termites (and ruminants) for digesting lignocellulosic material
- Compost heaps and forest floors are poorly explored
- In vitro protein engineering of promising enzymes
- Develop synthetic organic catalysts (for polysaccharides and lignin)



Enzymatic hydrolysis of cellulose is slow

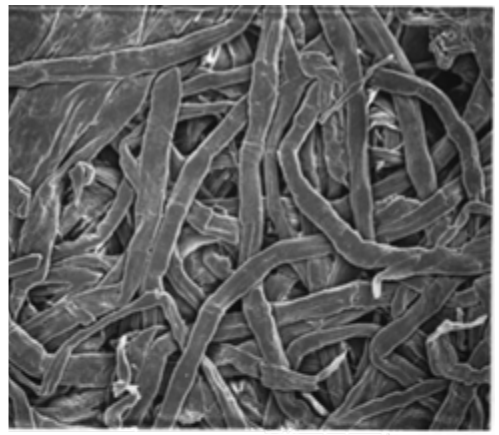


Skopec, Himmel, Matthews, Brady Protein Engineering 16, 1005

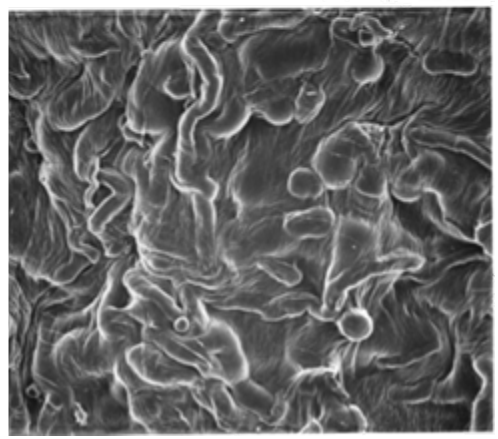
Dissolution of cellulose in an ionic liquid

(novel pretreatment methods may create fundamental changes)

1-Butyl-3-methylimidazolium chloride



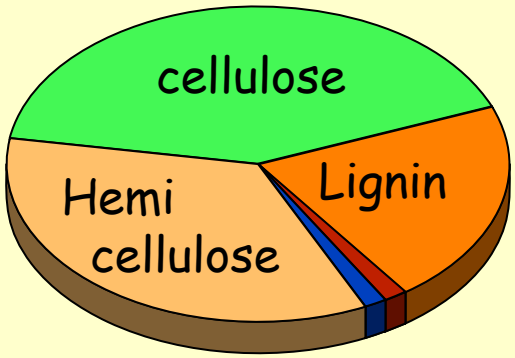
Untreated



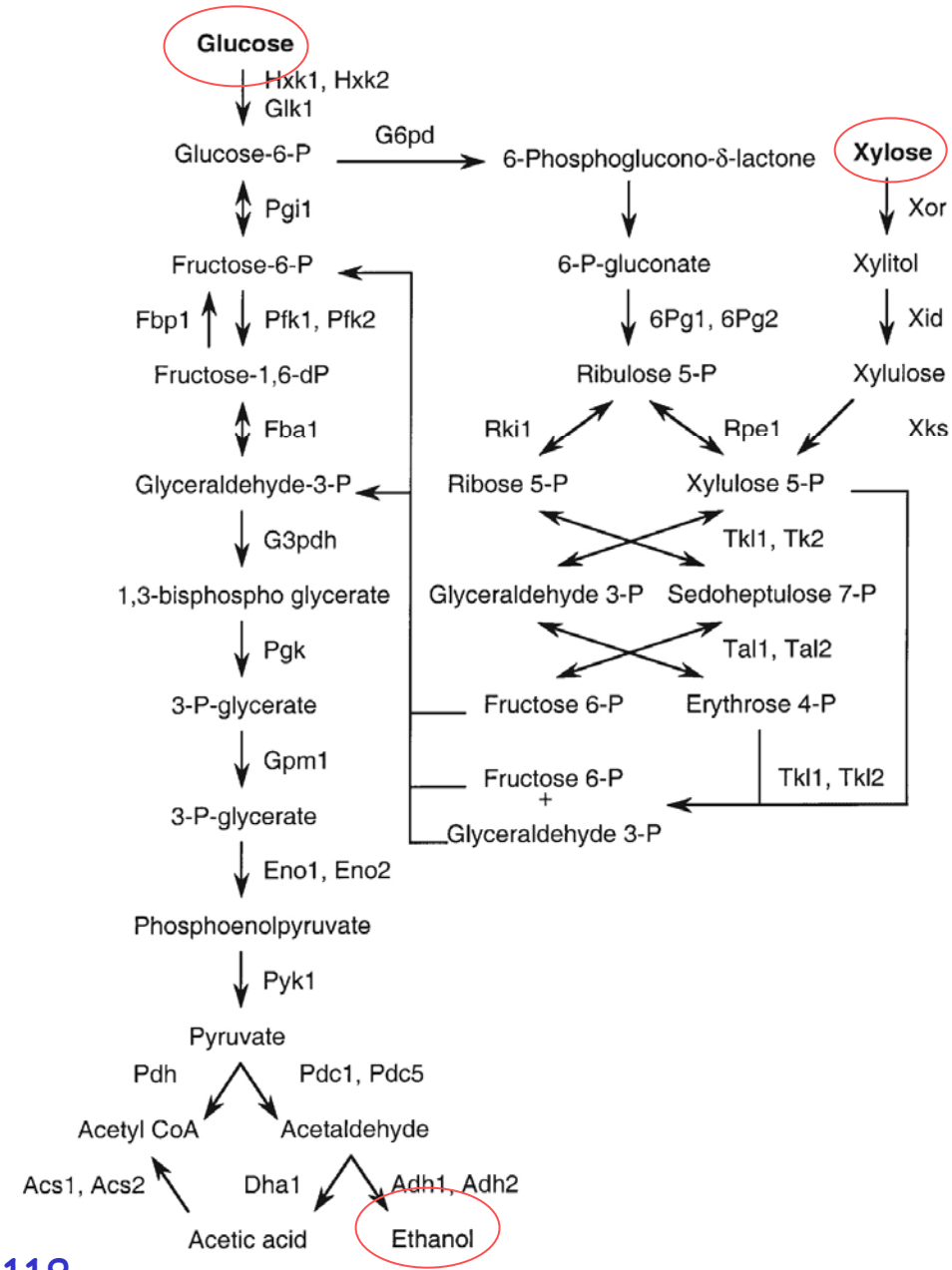
Treated

Swatloski, Spear, Holbrey, Rogers *J. Am. Chem. Soc.*, 124 (18), 4974 -4975, 2002

Fermentation of all sugars is essential

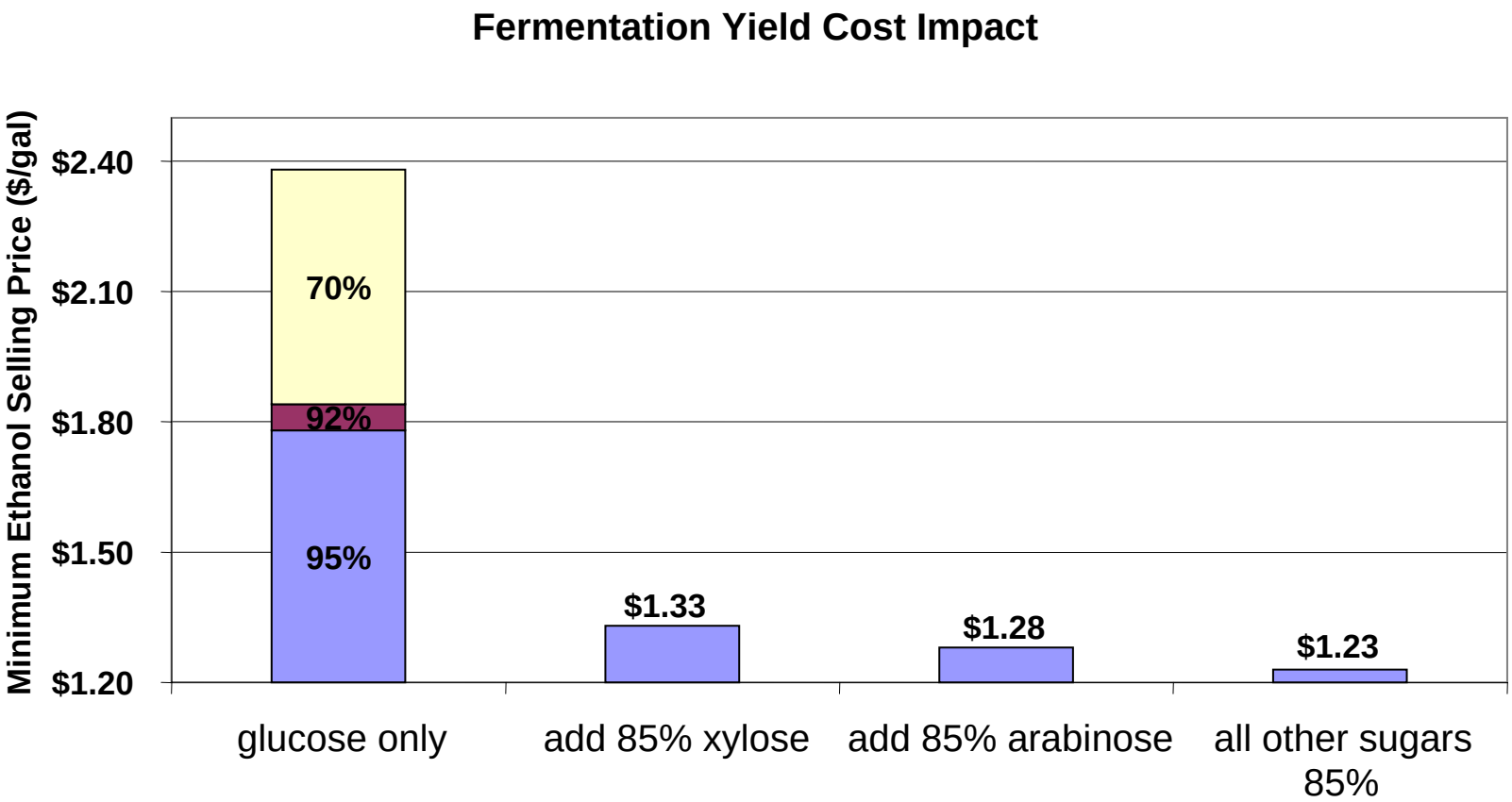


Typical grass composition



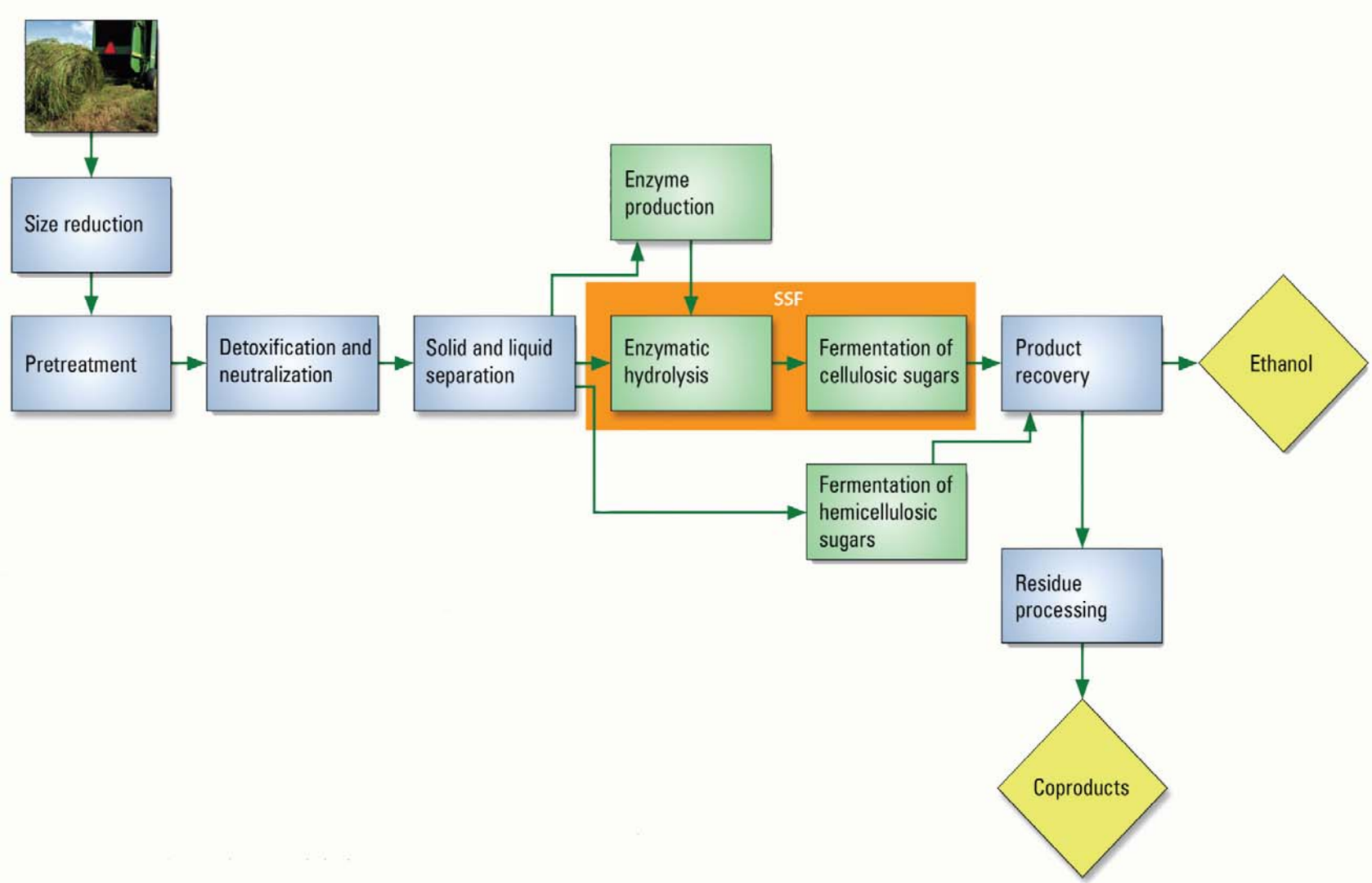
Jeffries & Shi Adv Bioch Eng 65,118

Saccharification & Fermentation



NREL

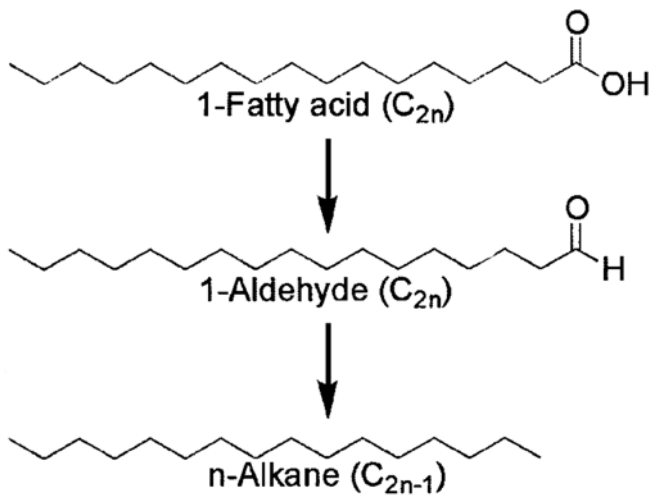
Steps in cellulosic ethanol production



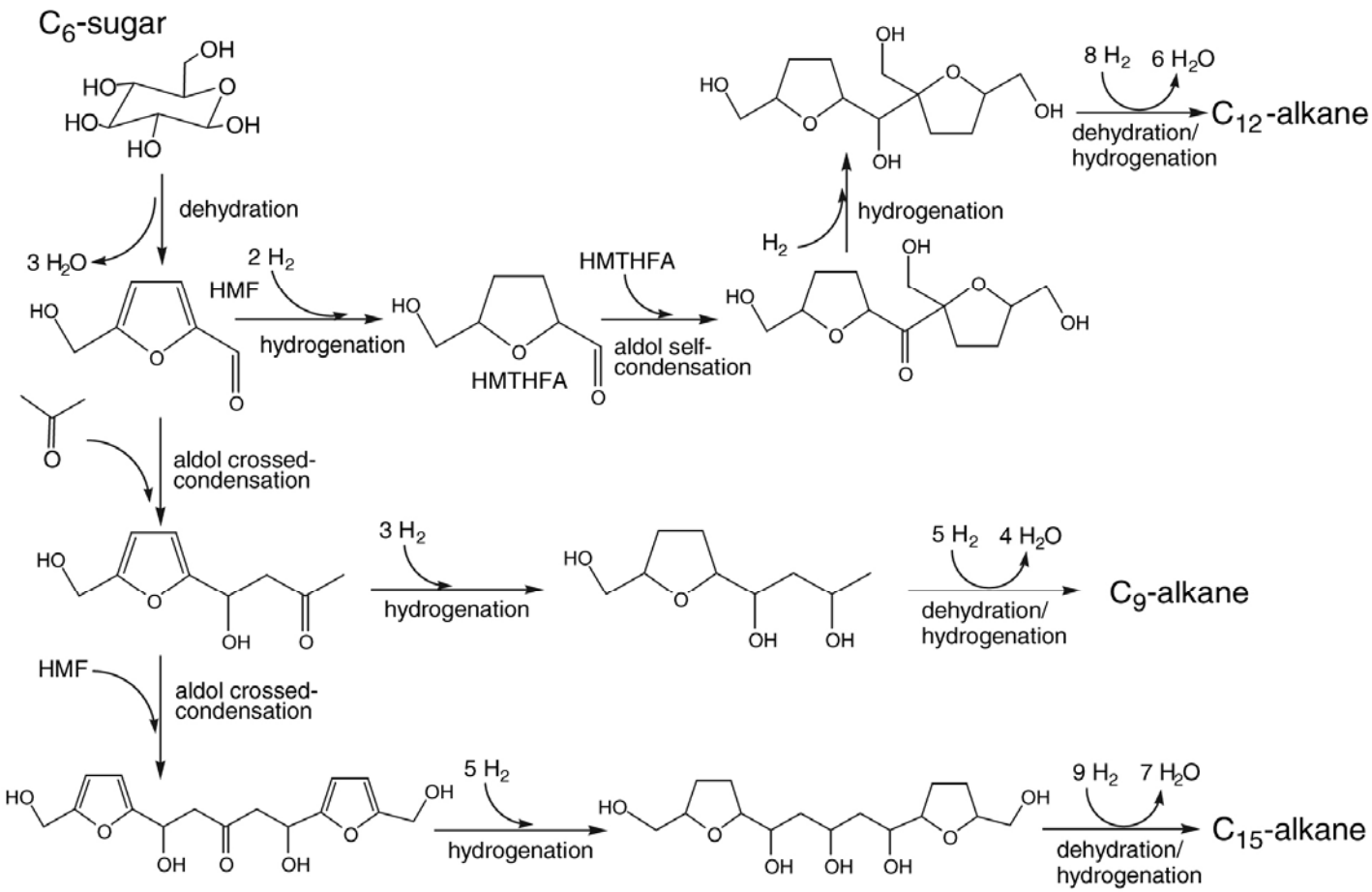
From: Breaking the Biological Barriers to Cellulosic Ethanol

Nature offers many alternatives to ethanol

- Plants, algae, and bacteria synthesize alkanes, alcohols, waxes
- Production of hydrophobic compounds would reduce toxicity and decrease the energy required for dehydration

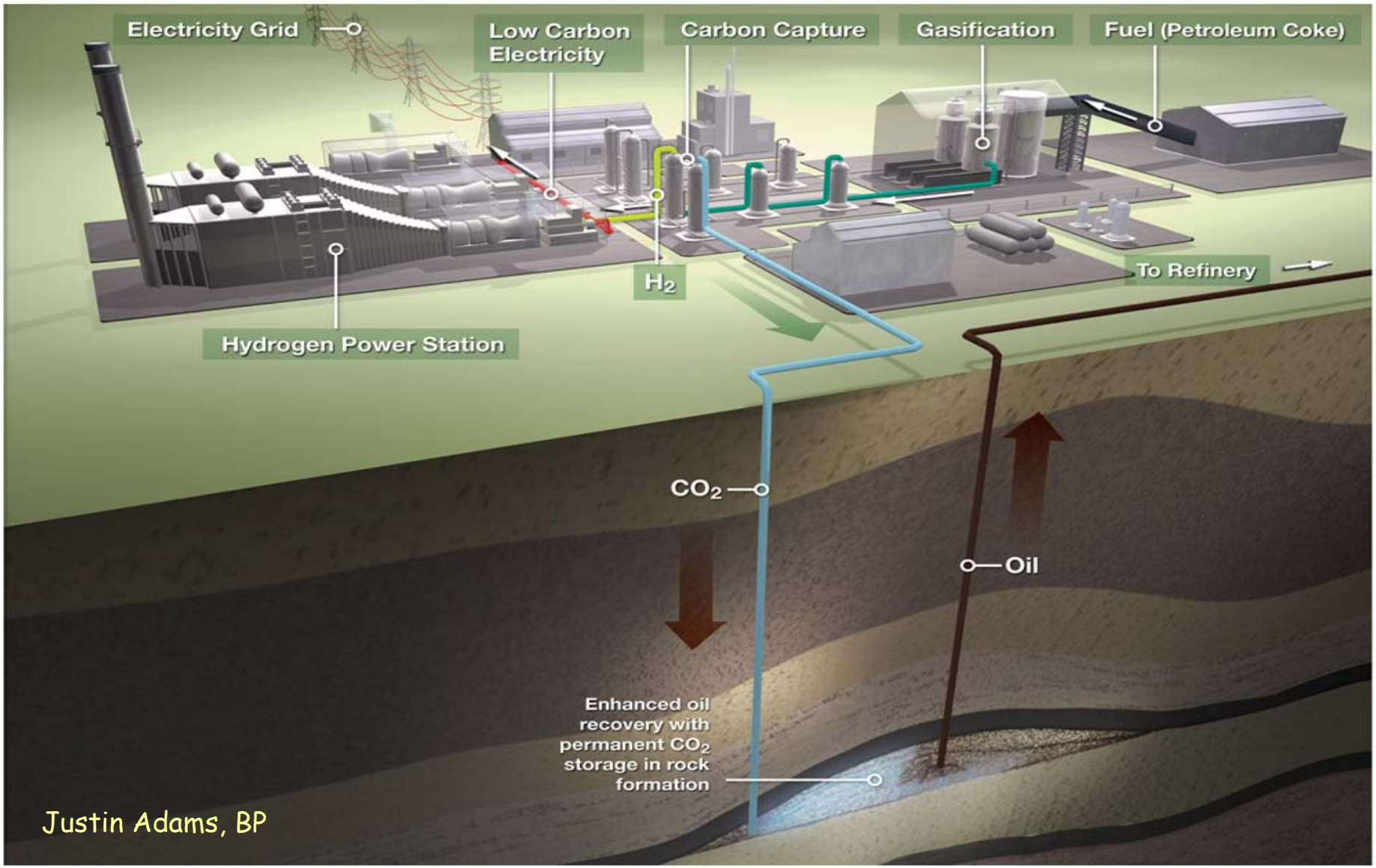


Conversion of sugar to alkanes



Huber et al., (2005) Science 308,1446

The "hydrogen economy"

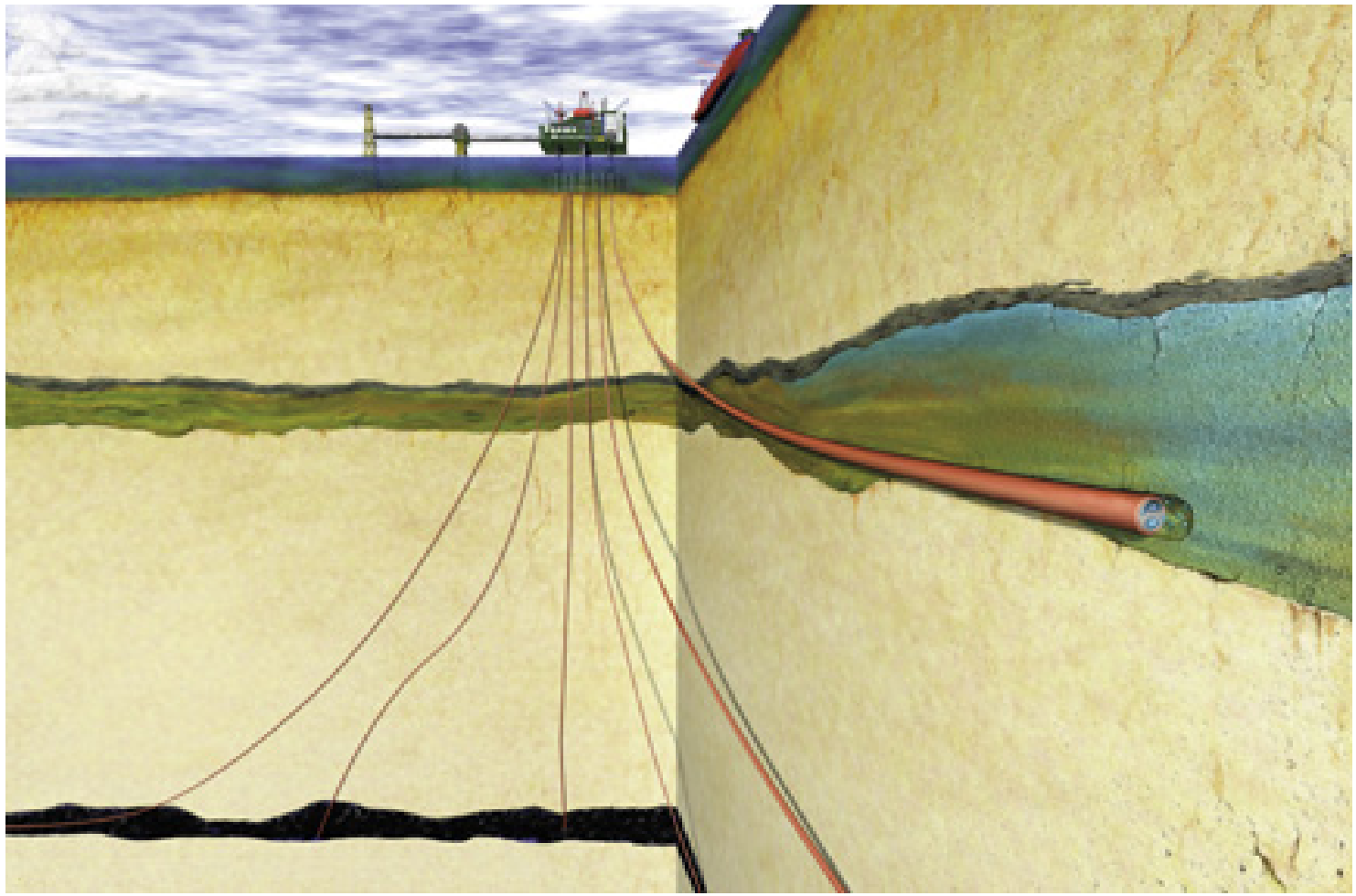


Justin Adams, BP

The Sleipner Experiment

1 million tons/y; capacity 600 B tons
7000 such sites needed

1000 M



www.agiweb.org/geotimes

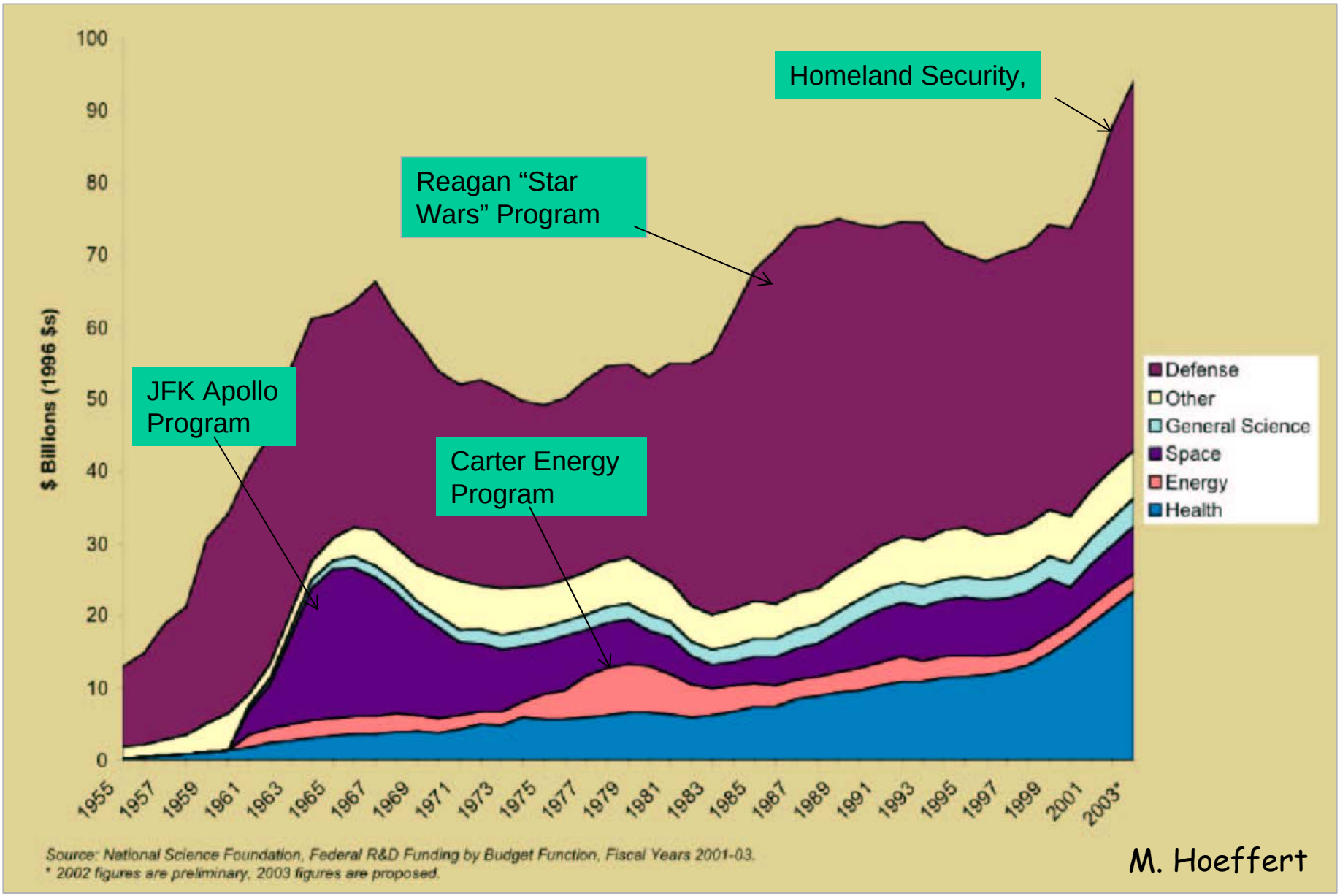
Summary of priorities

- Develop energy crops and associated agronomic practices
- Identify or create more active catalysts for conversion of biomass to sugars
- Develop industrial microorganisms that ferment all sugars
- Develop new types of microorganisms that produce and secrete hydrophobic compounds

The Energy Bioscience Institute

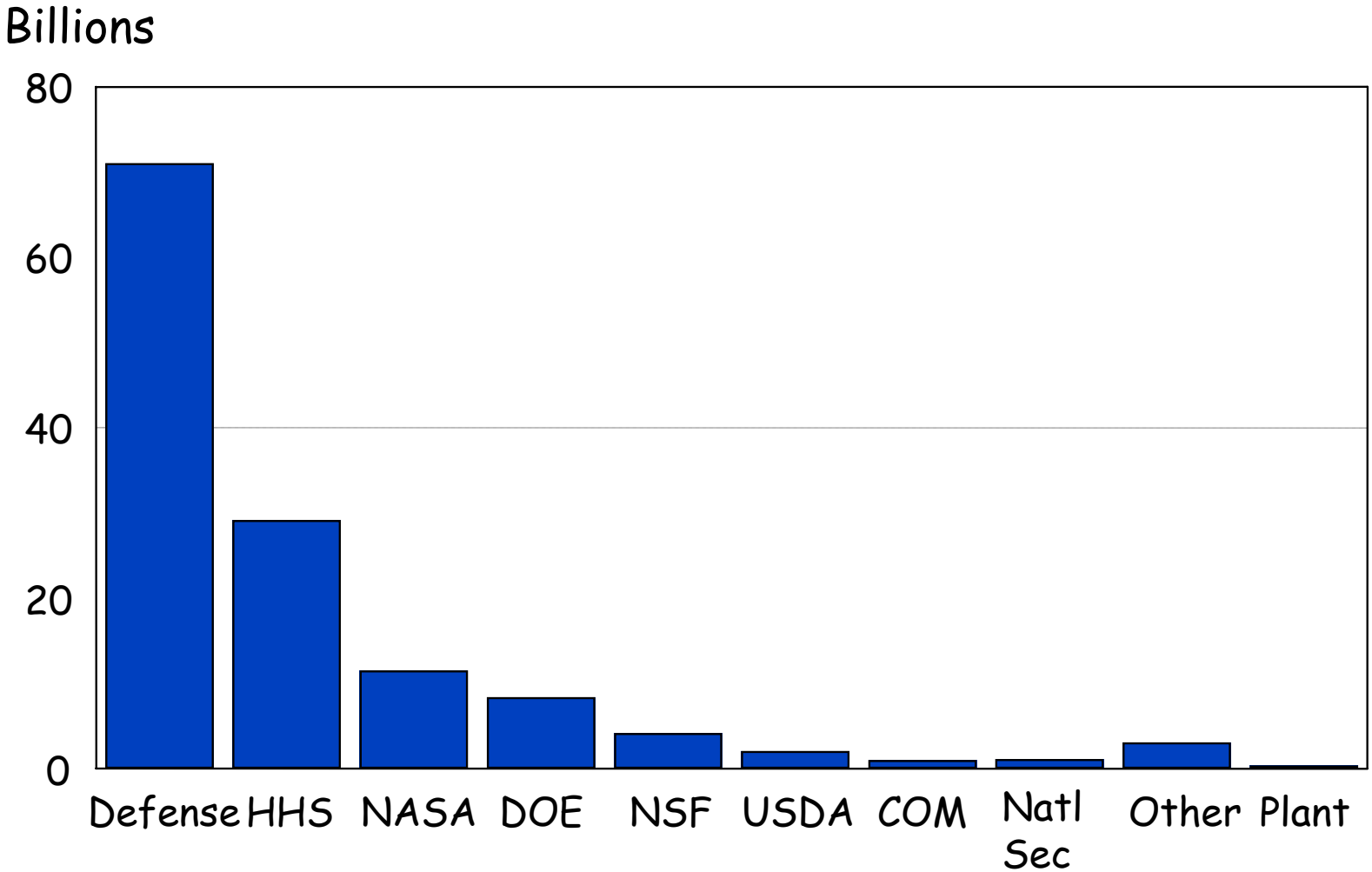
- Partnership between UCB, UI, LBL
- BP has committed $500M over 10 years
- Goals include elimination of bottlenecks to biofuels, development of improved biotechnologies for fuel production, and education of scientists and engineers across the relevant disciplines

HISTORY OF US FEDERAL GOVERNMENT R & D

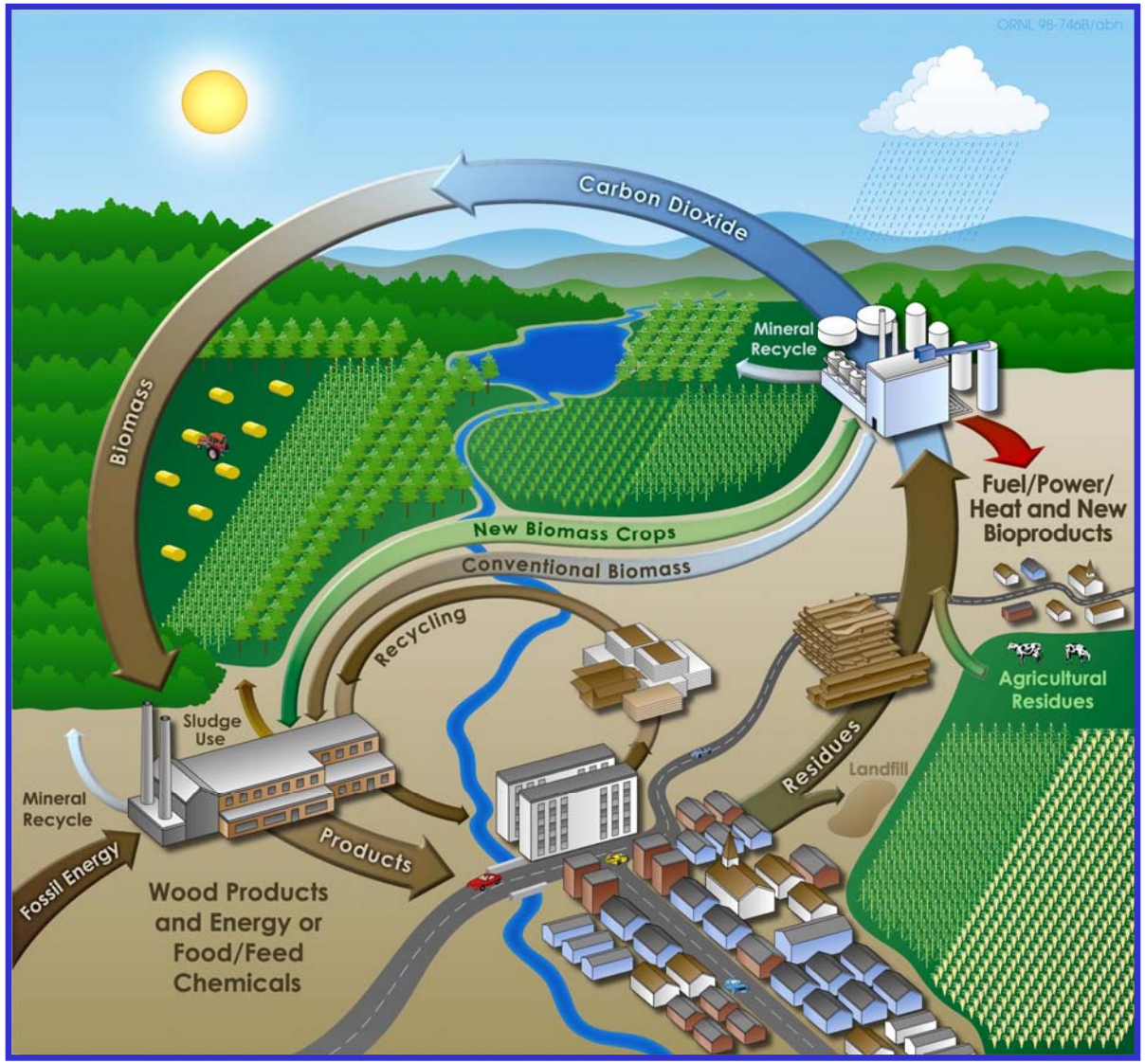


M. Hoeffert

Federal Research Budget 2006



A vision of the Future



http://genomicsgtl.energy.gov/biofuels/index.shtml