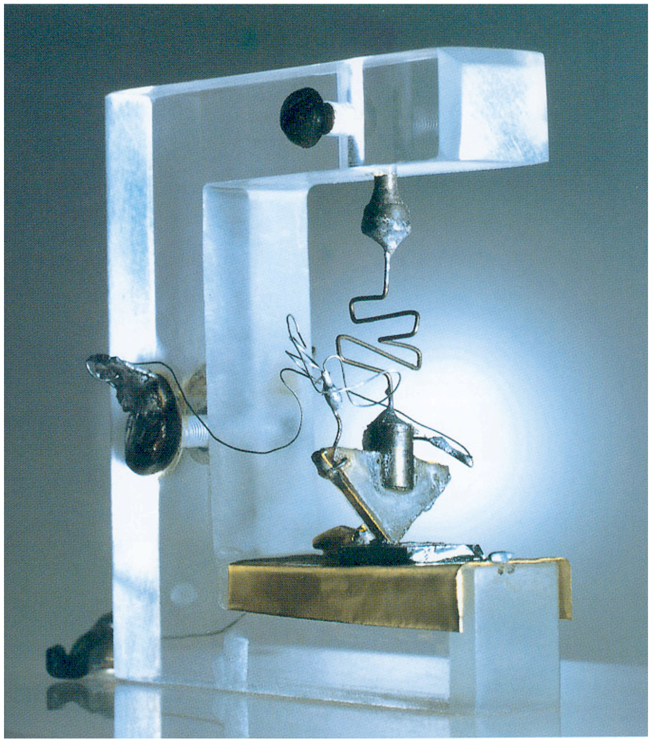
Evolution of Biofuels

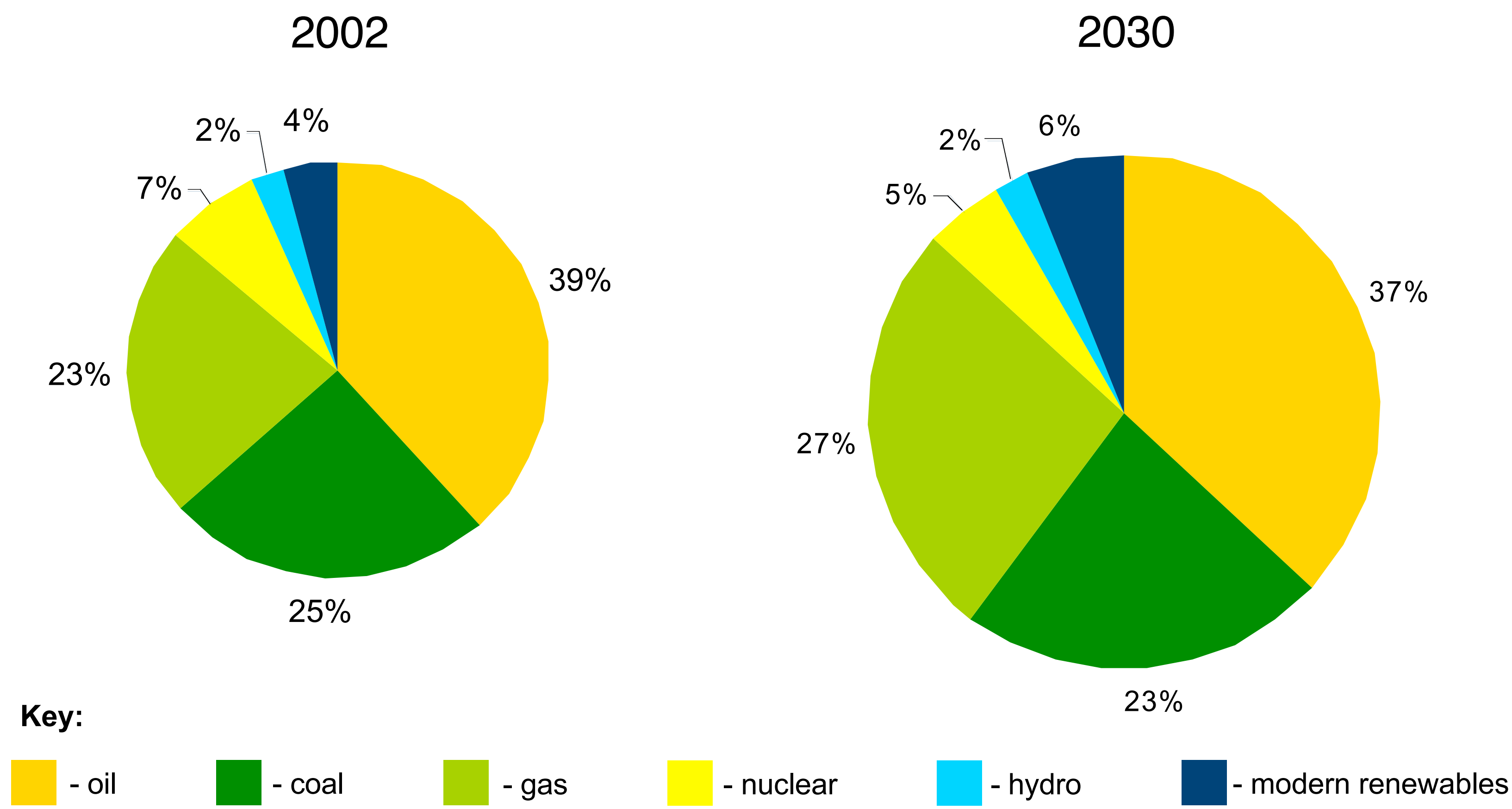


Chris Somerville
Carnegie Institution, Stanford University, LBNL.
EBI

Current and predicted energy use

Current use 13 TW

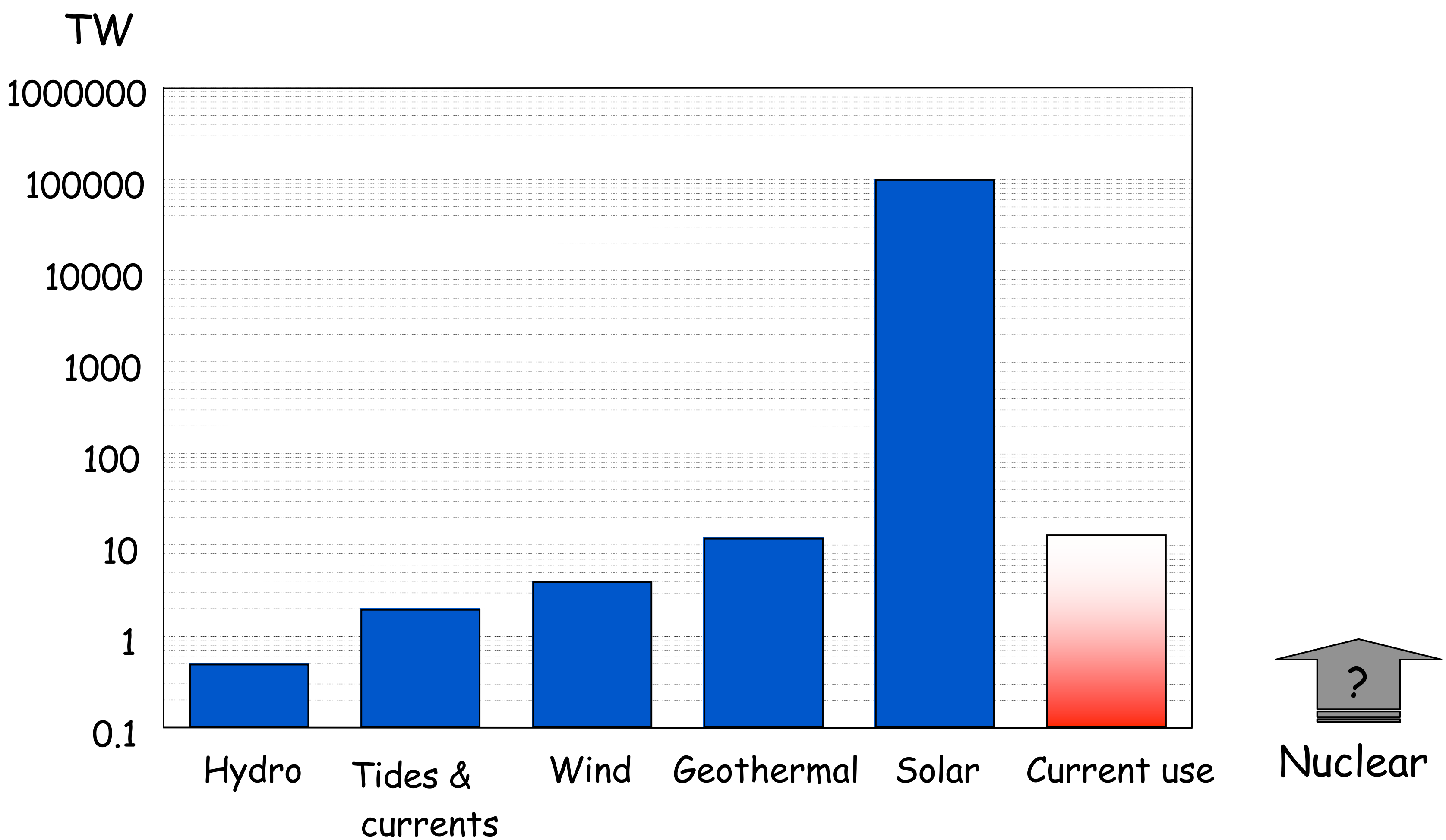
Global Primary Energy Supply by Fuel:*



* - excludes traditional biomass

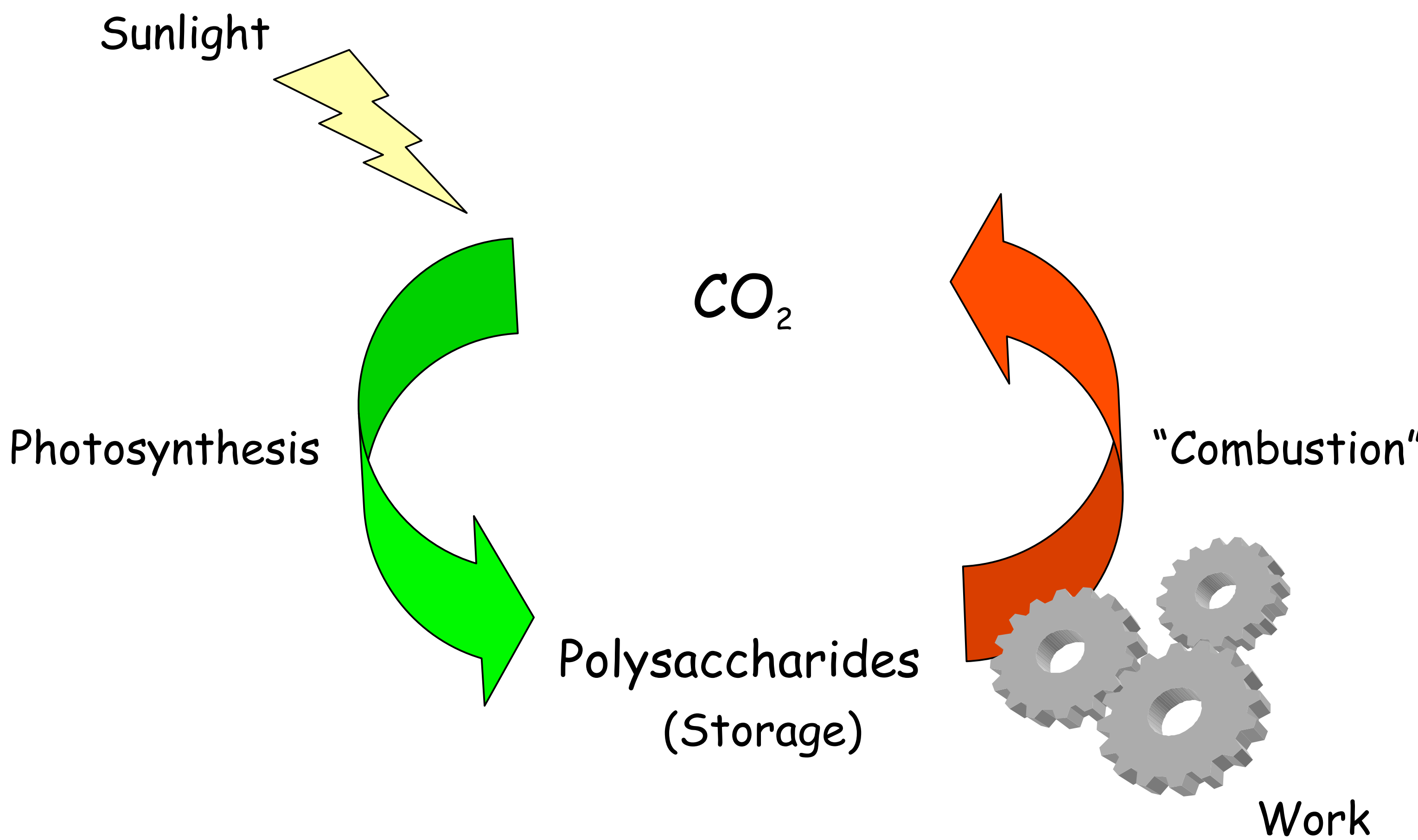
Source: IEA 2004, Jim Breson BP

Potential of carbon-free energy sources

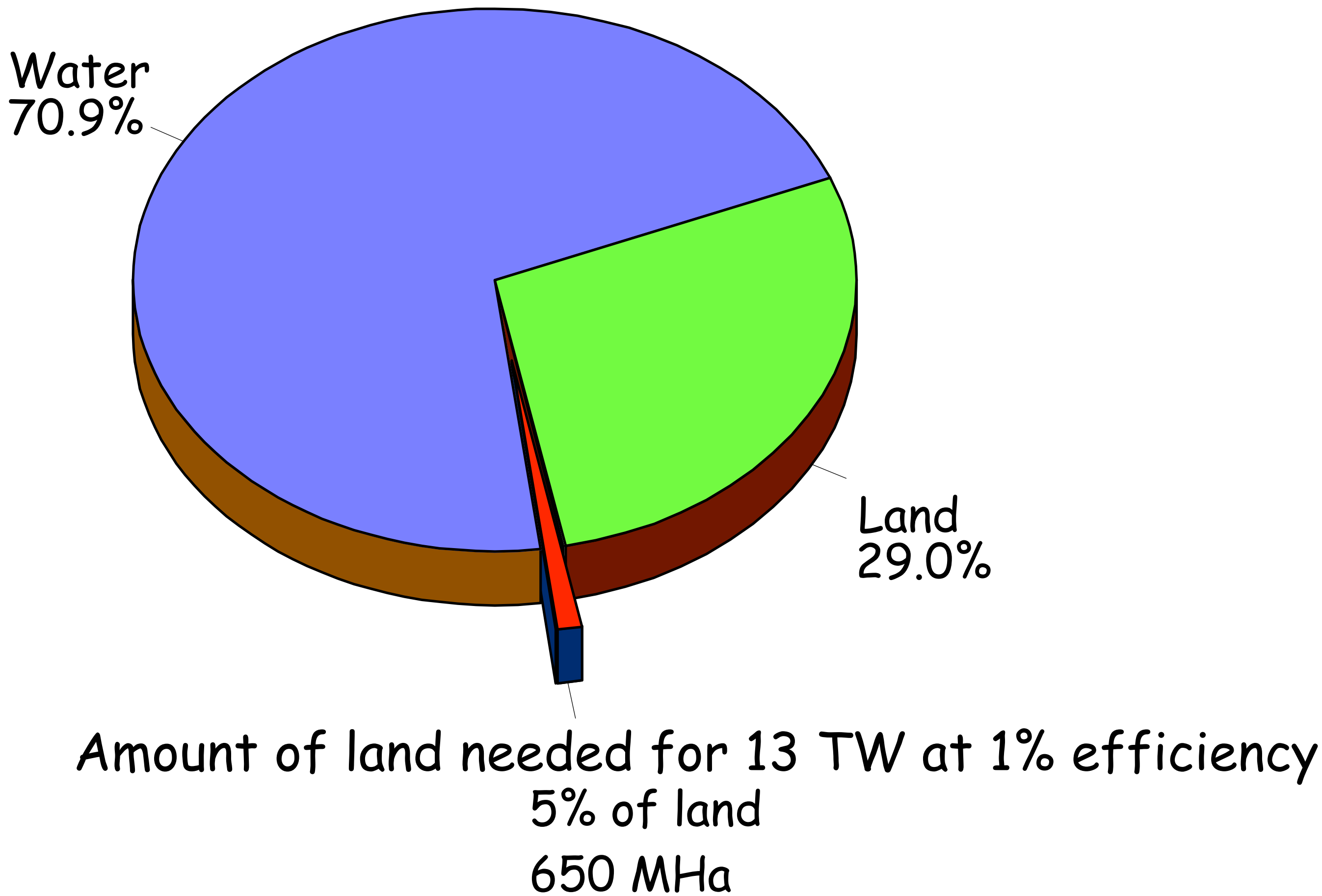


From: Basic Research Needs for Solar Energy Utilization, DOE 2005

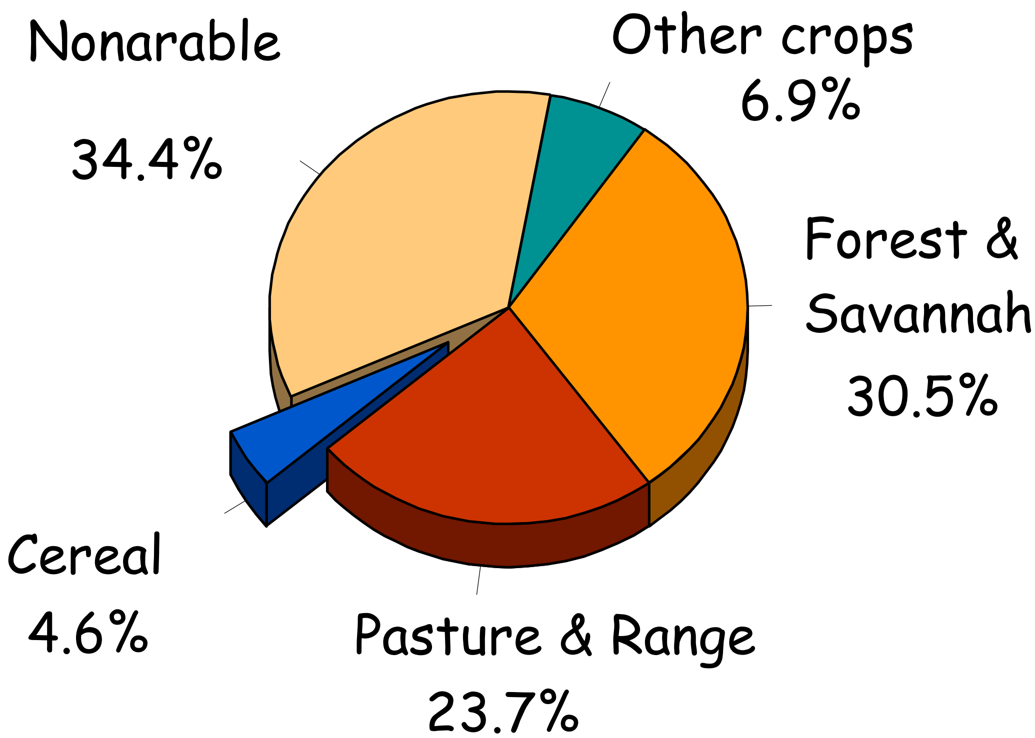
Combustion of biomass provides carbon neutral energy



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



Land Usage



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

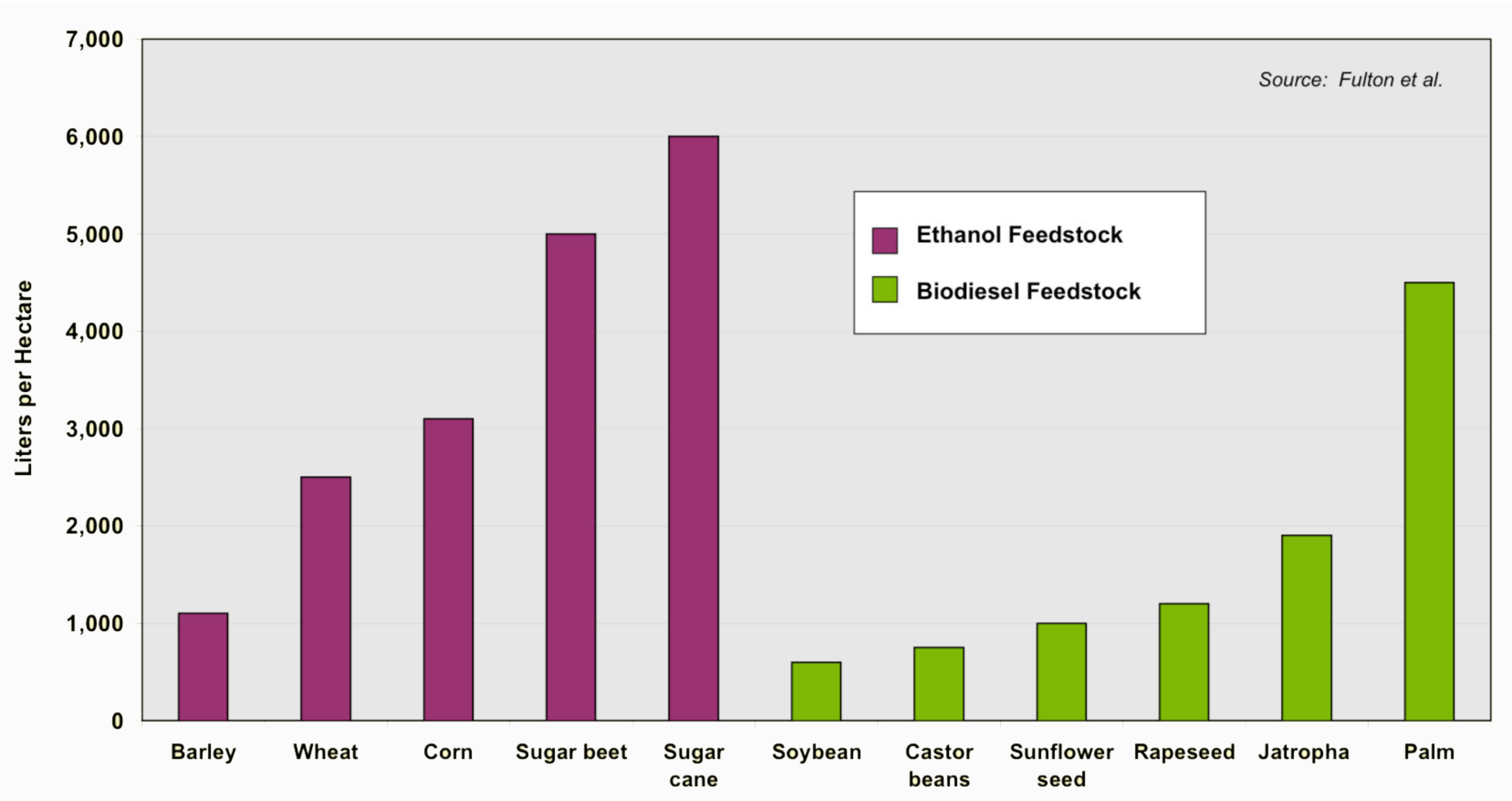
Types of biofuels

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

Overview of Brazil sugarcane

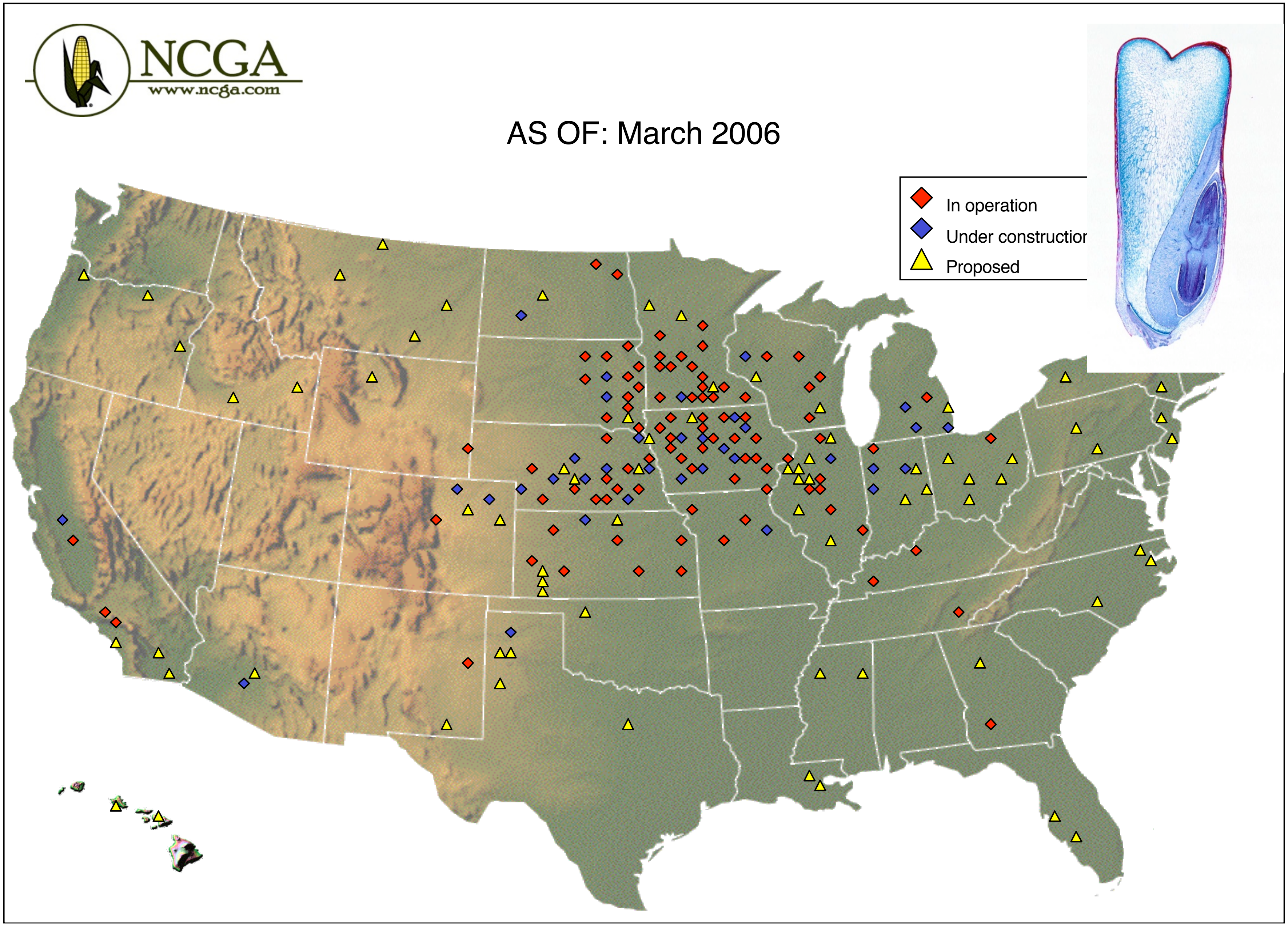
- 2007-08 harvest 528 MMT
- ~8 M Ha planted by 2008
- ~20 B liters ethanol, 2007
- ~80-120 T/Ha
- ~6400 L ethanol/Ha
- ~333 mills, 100 planned
- Plantings last 5 y, cut one per year
- Large mill
  - 22,000 tons/day
  - 1500 truck loads/day

Biofuel yields of various feedstocks



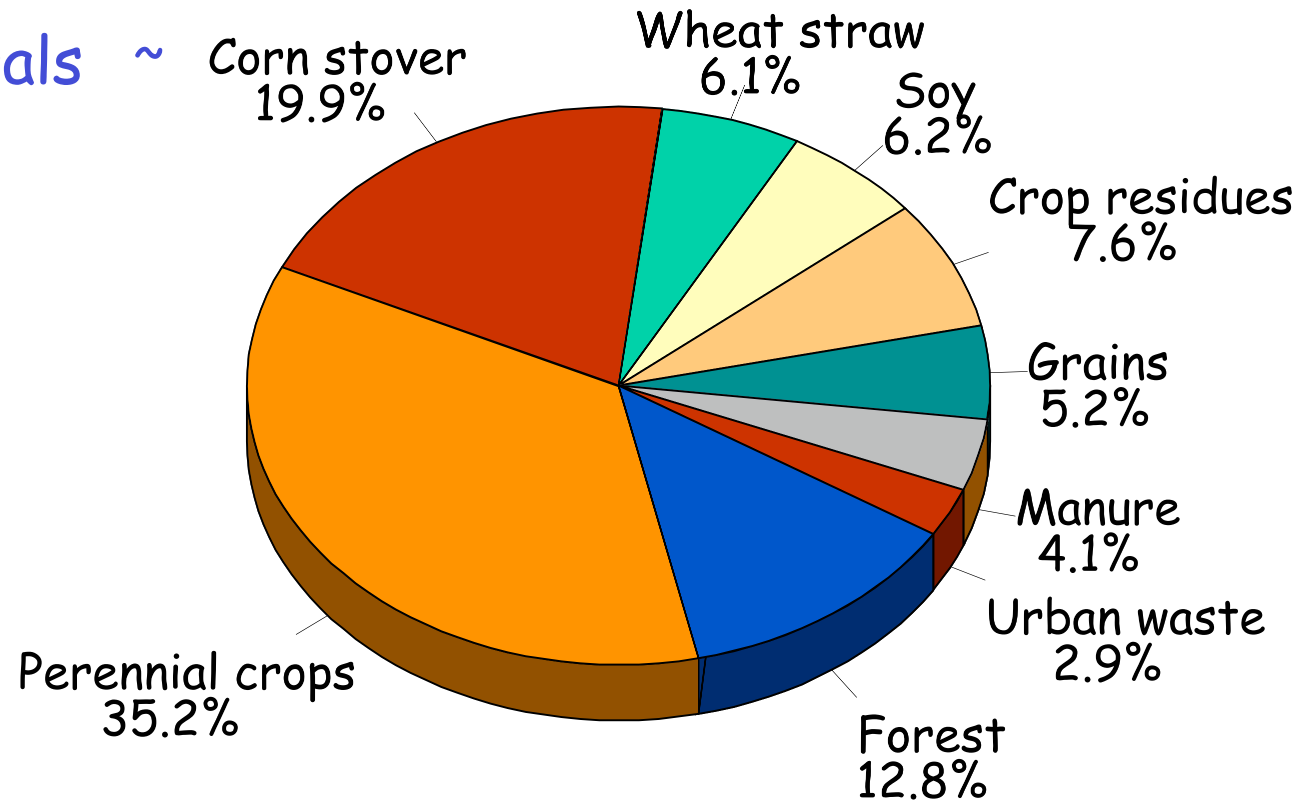
Worldwatch 2006

US Biofuel Production has Expanded Rapidly



US Biomass inventory = 1.3 billion tons

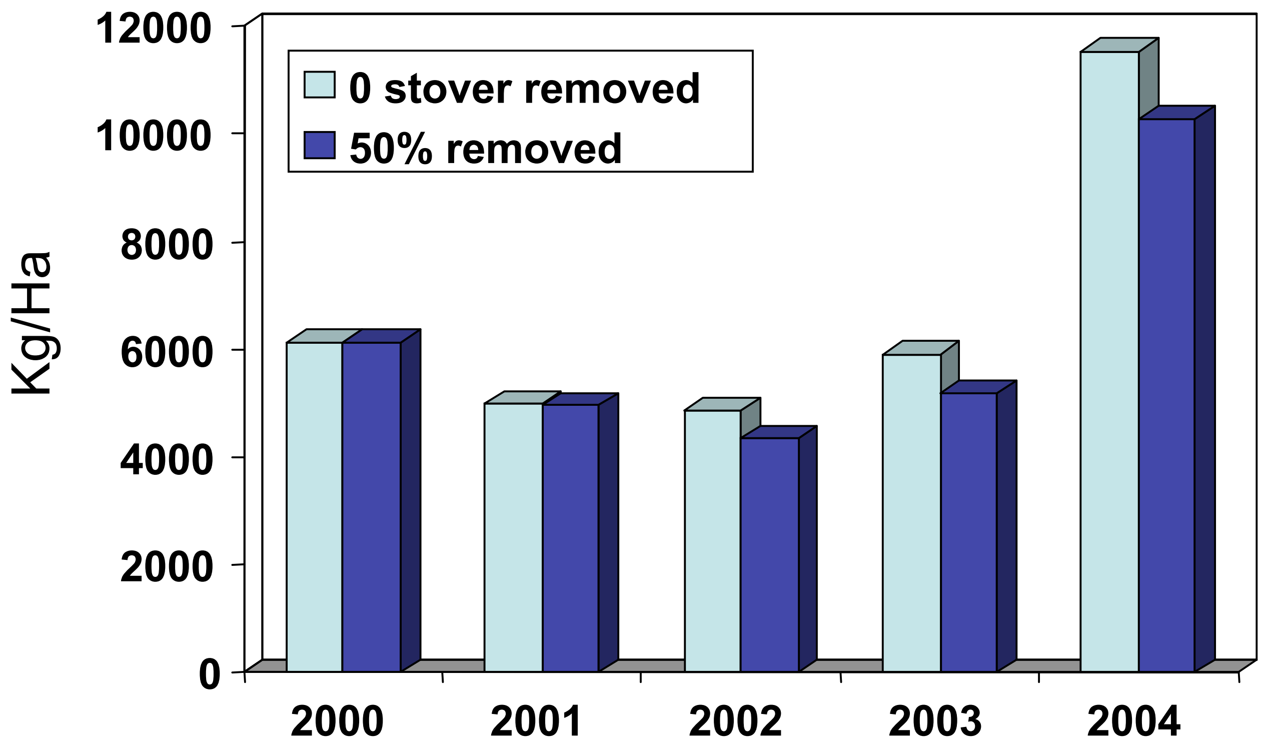
26 B gals ~



From: Billion ton Vision, DOE & USDA 2005

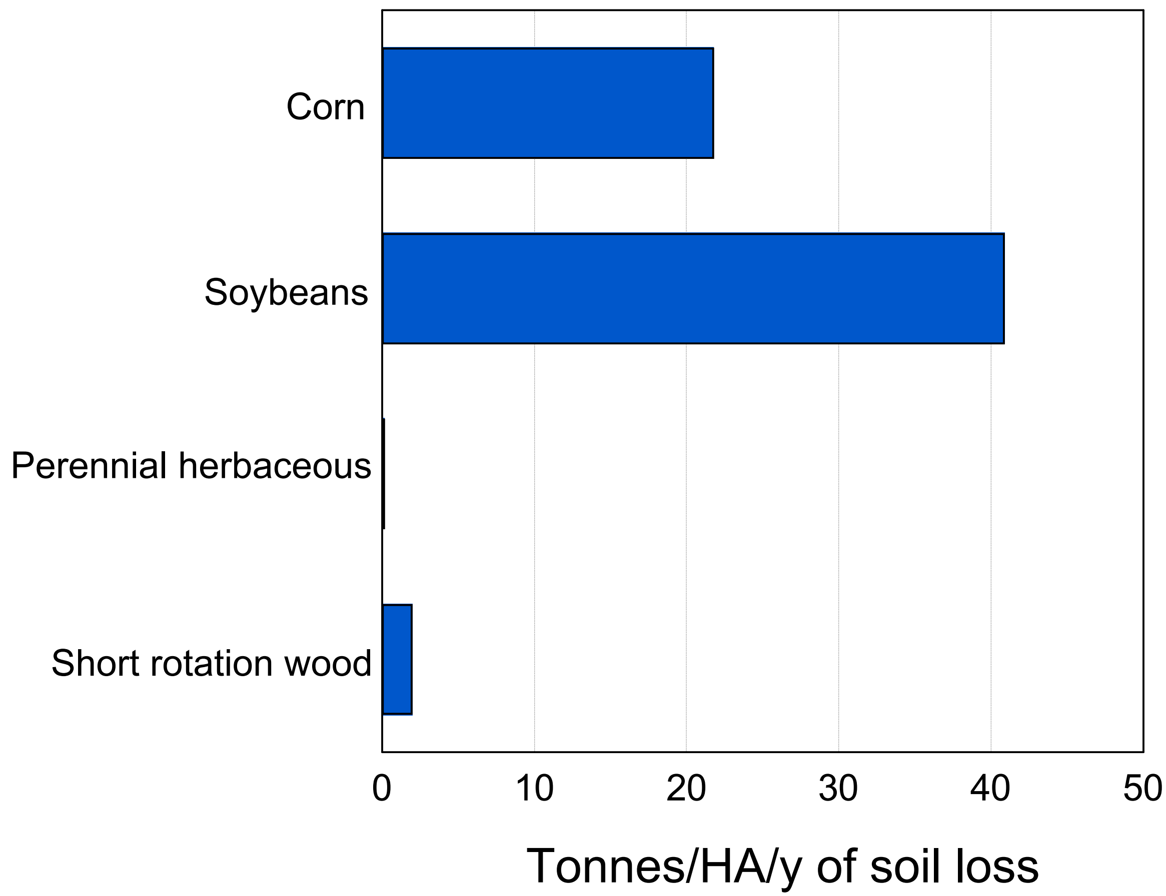
Effect of 50% stover removal on corn grain yields in eastern NE.

(120kg N/ha)



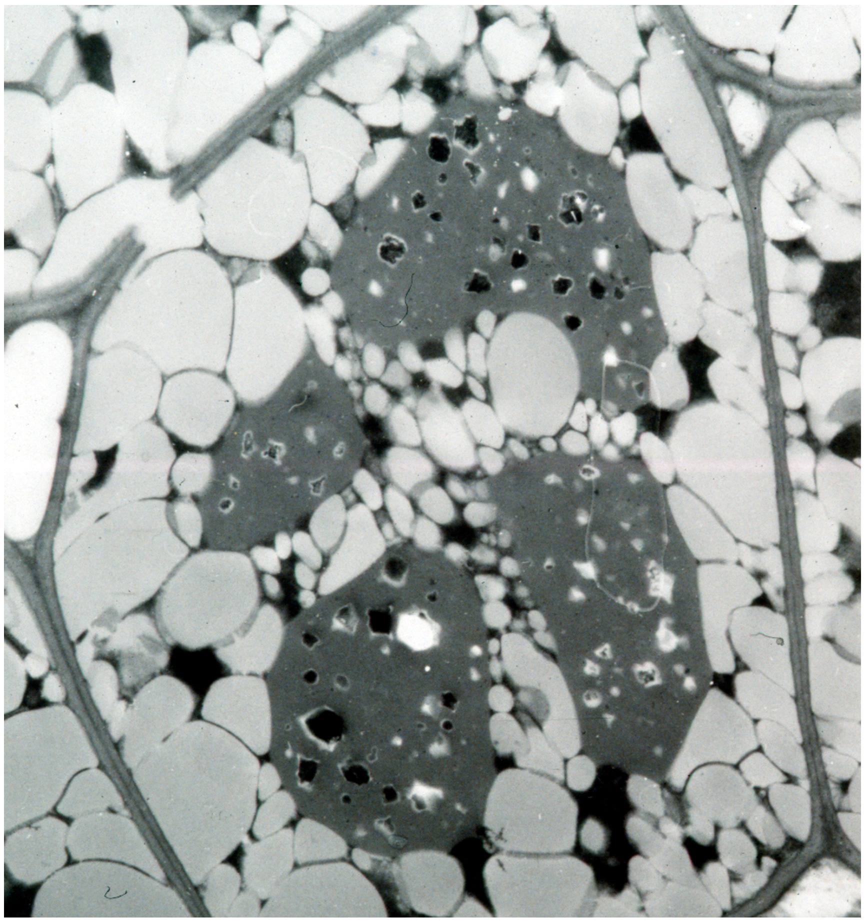
K. Vogel et al., unpublished

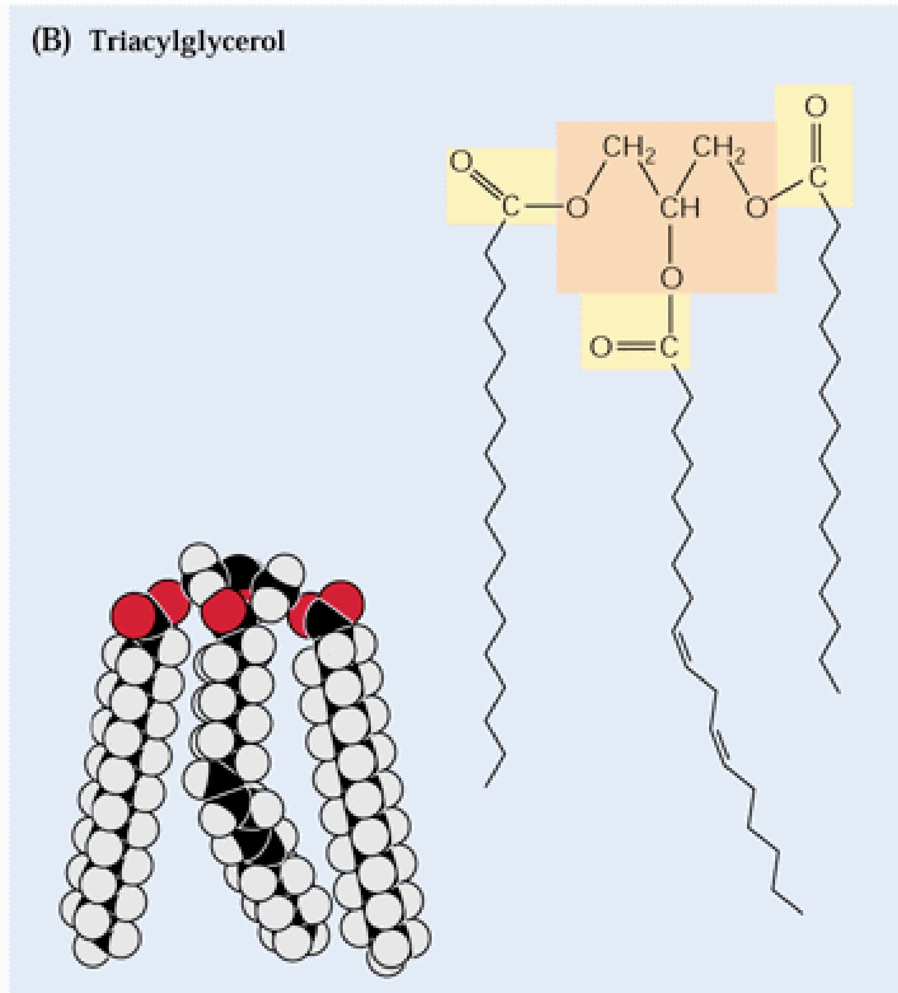
Perennials have little or no erosion



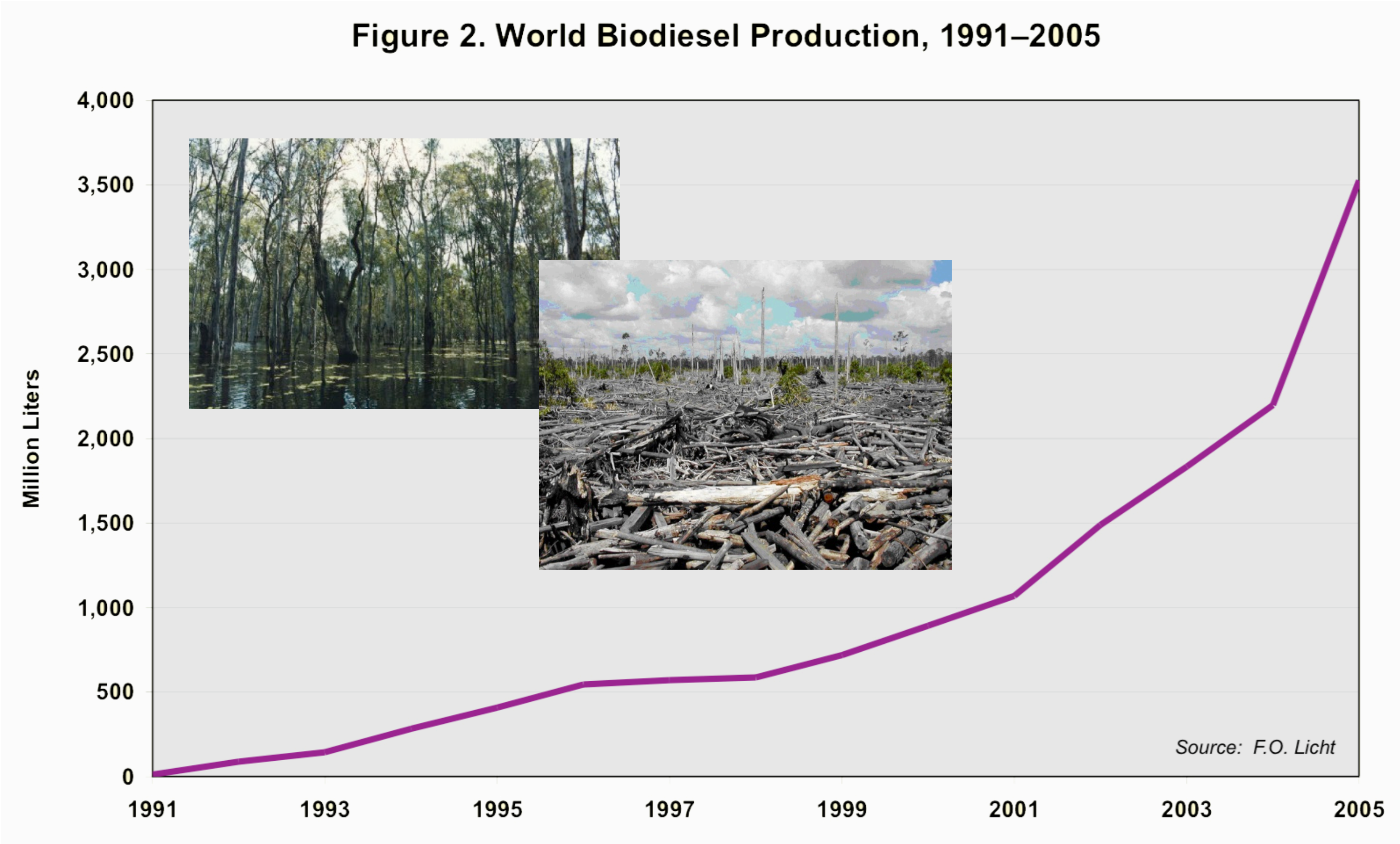
From Oliveira et al in: Jones and Walsh (eds) Miscanthus for Energy and Fibre, 2001

Some plants accumulate oil



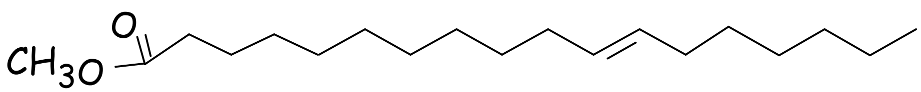


Biodiesel has been expanding rapidly

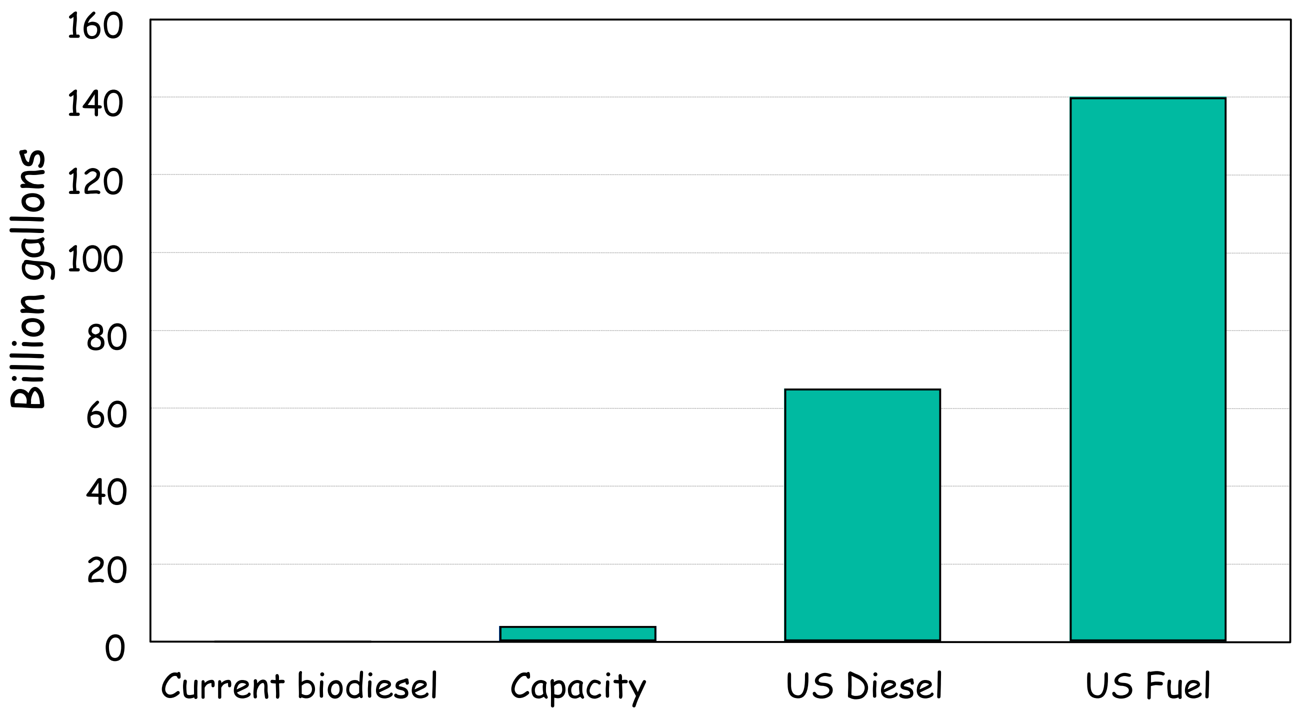


Worldwatch 2006 & Louise Fresco

Limited potential of biodiesel



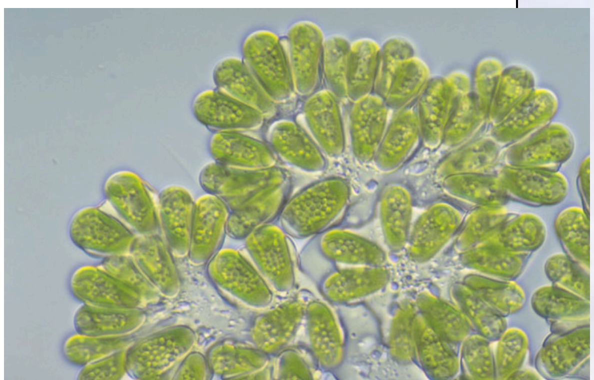
Biodiesel



65 biodiesel companies in operation, 50 in construction 2006

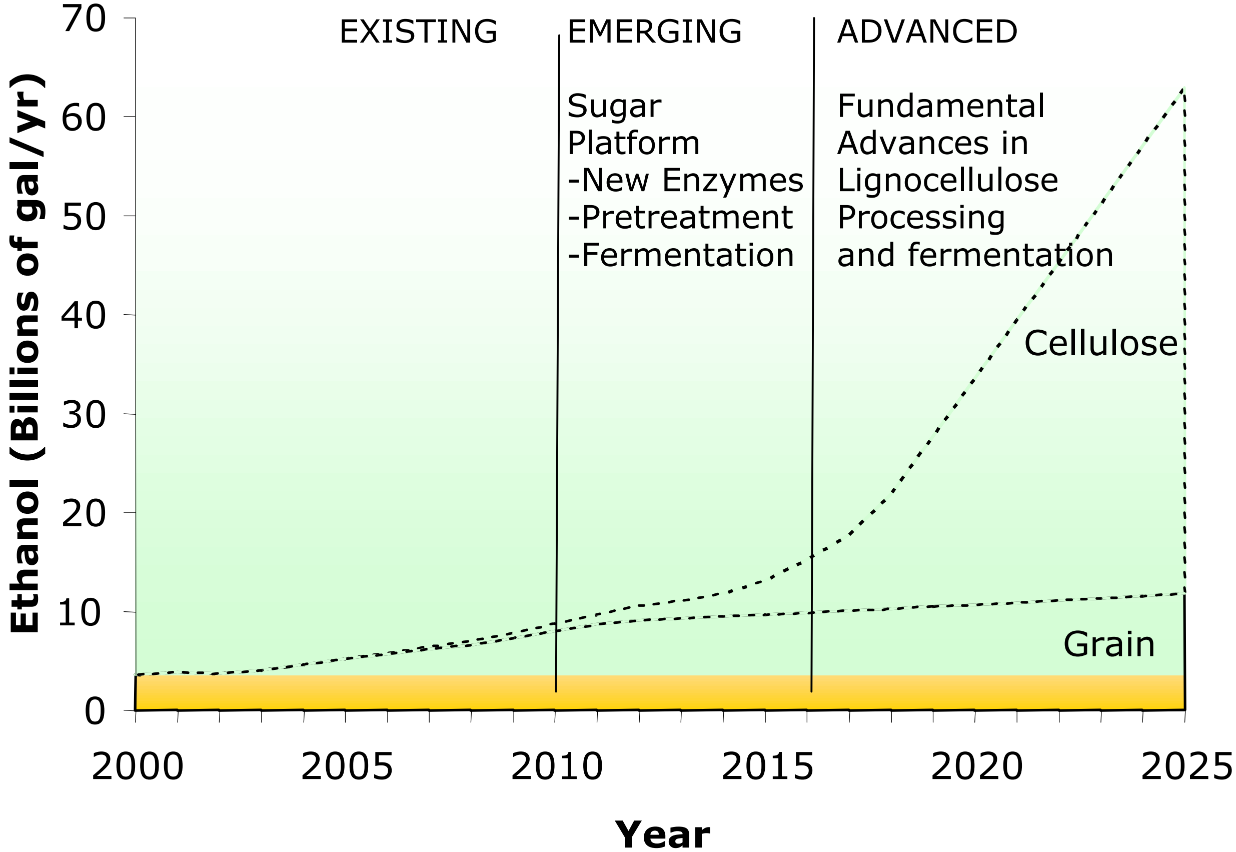
Use of algae could enable saline cultivation

Greenfuel bioreactor



http://news.com.com/Photos+Betting+big+on+biodiesel/2009-1043_3-5714336.html?t

Cellulosic fuels are expected to become the dominant source of biofuels



Modified from Richard Bain, NREL

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.

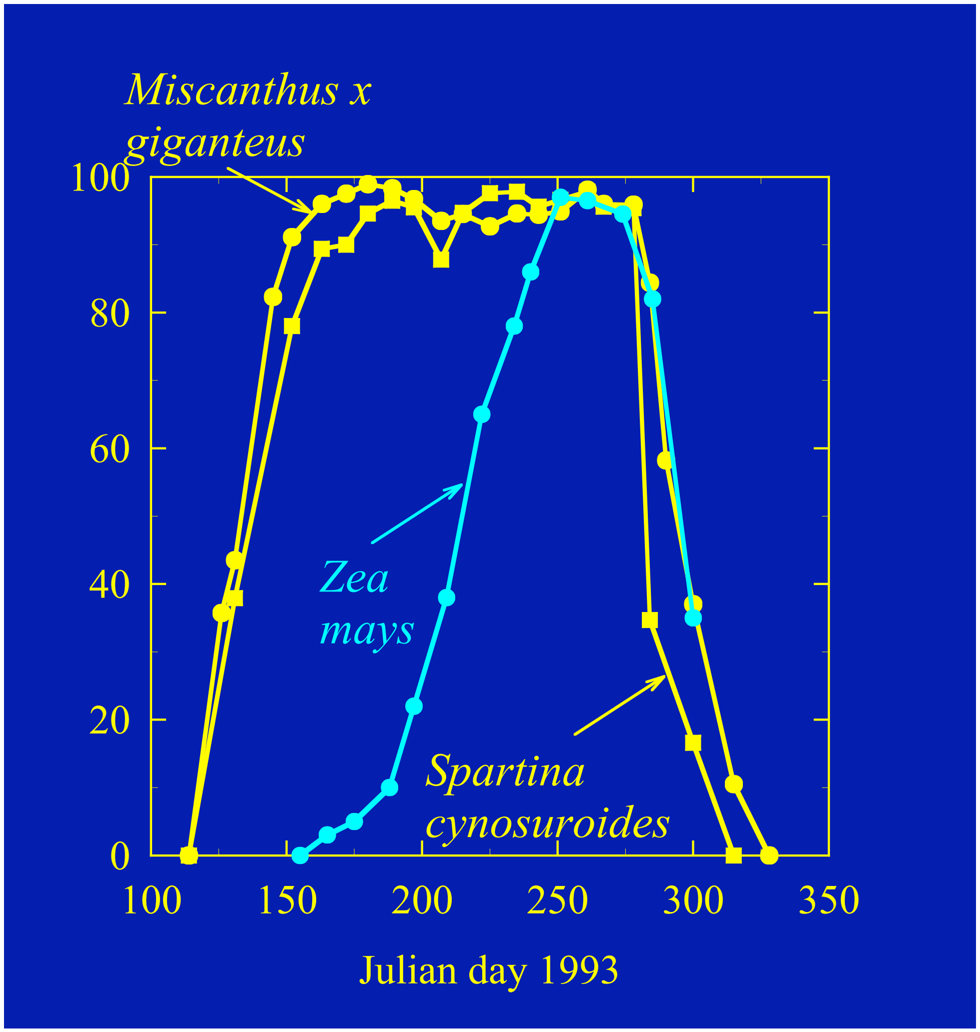
Worldwatch, 2006

>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

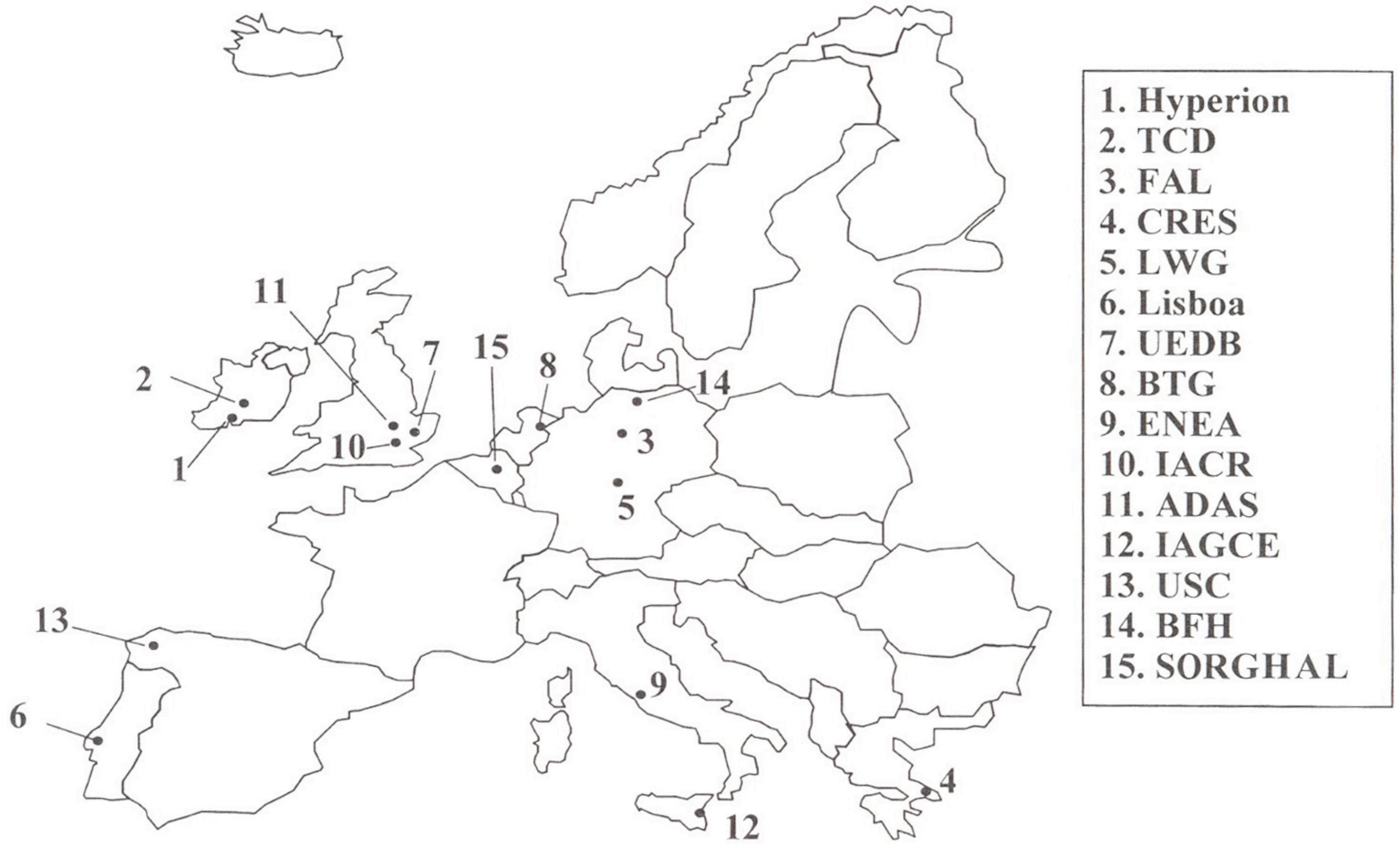
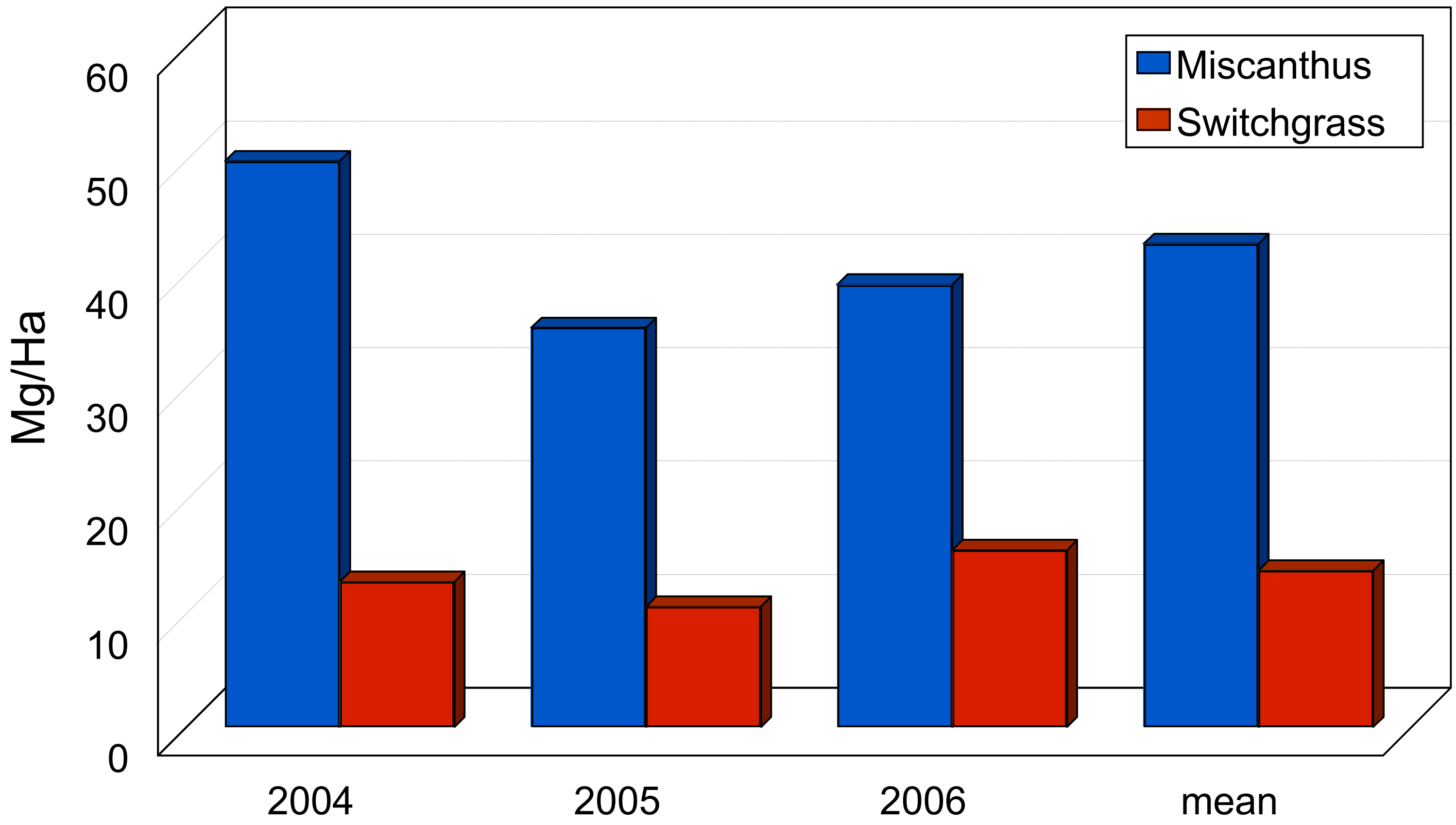


Figure 4.6. Geographical distribution of the trials in the European Miscanthus *Productivity Network. See Preface for key to acronyms*

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

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.

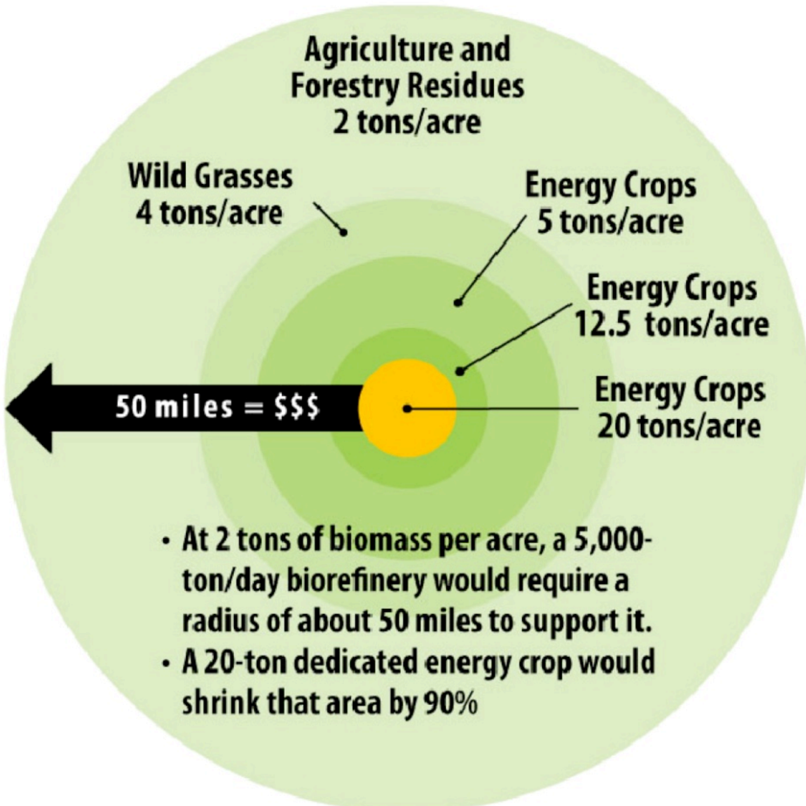
From Lewandowski et al., Biomass & Bioenergy 25,335

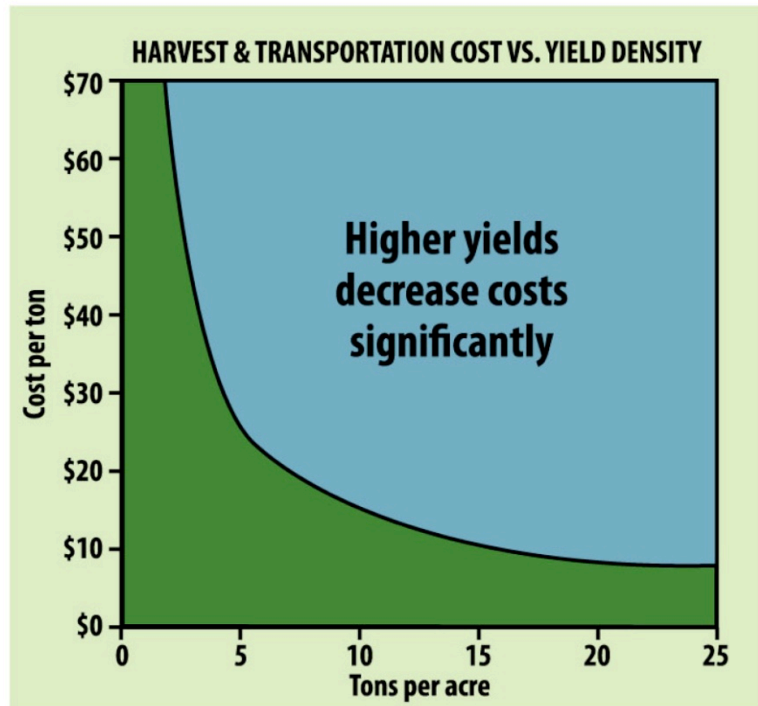
Theoretical yield of cellulosic ethanol from various feedstocks

Feedstock	Theoretical Yield in gallons per dry ton of feedstock
Corn Grain	124.4
Corn Stover	113.0
Rice Straw	109.9
Cotton Gin Trash	56.8
Forest Thinnings	81.5
Hardwood Sawdust	100.8
Bagasse	111.5
Mixed Paper	116.2

Wes Herman, GCEP

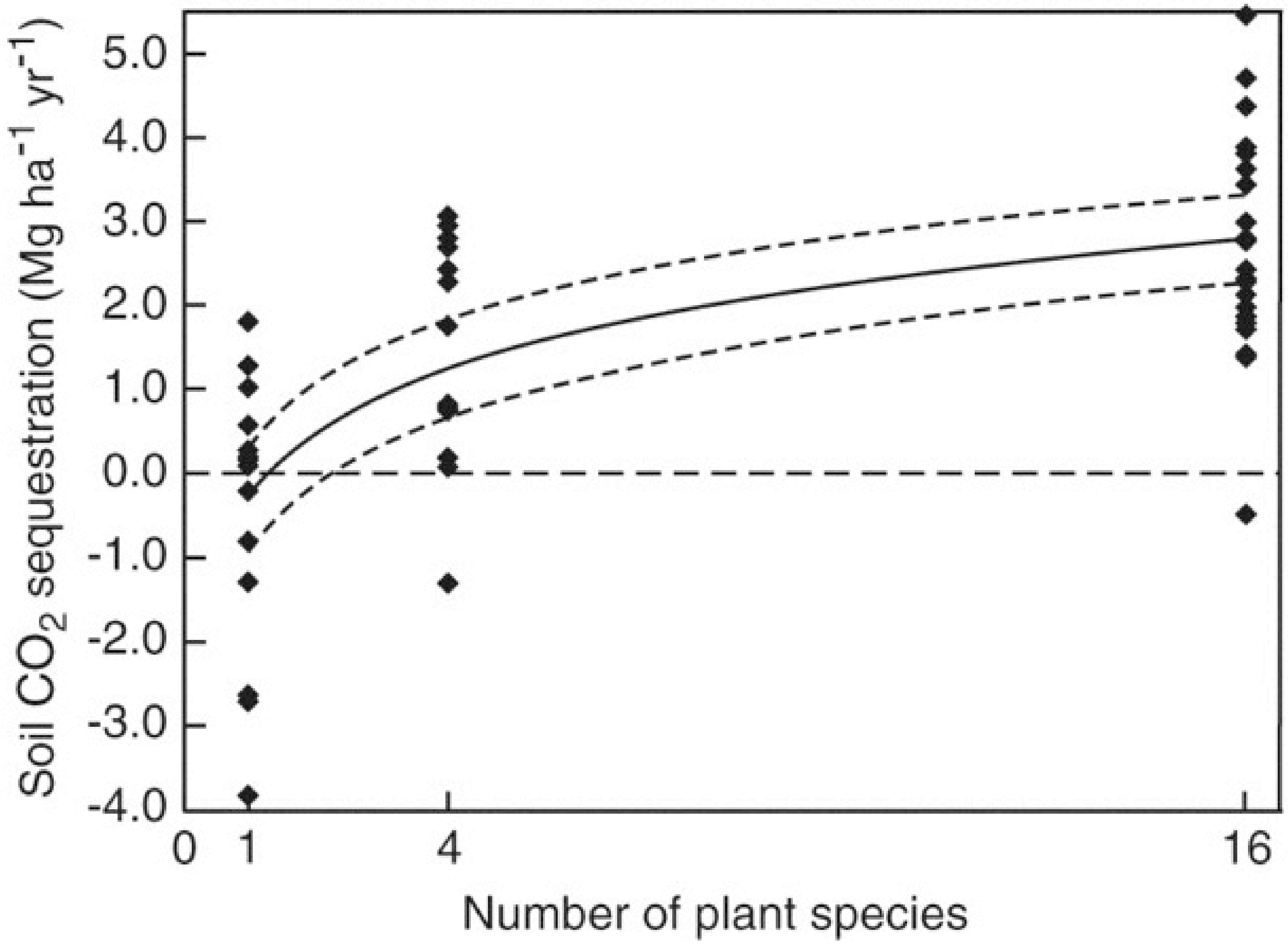
High yield decreases transportation and land costs





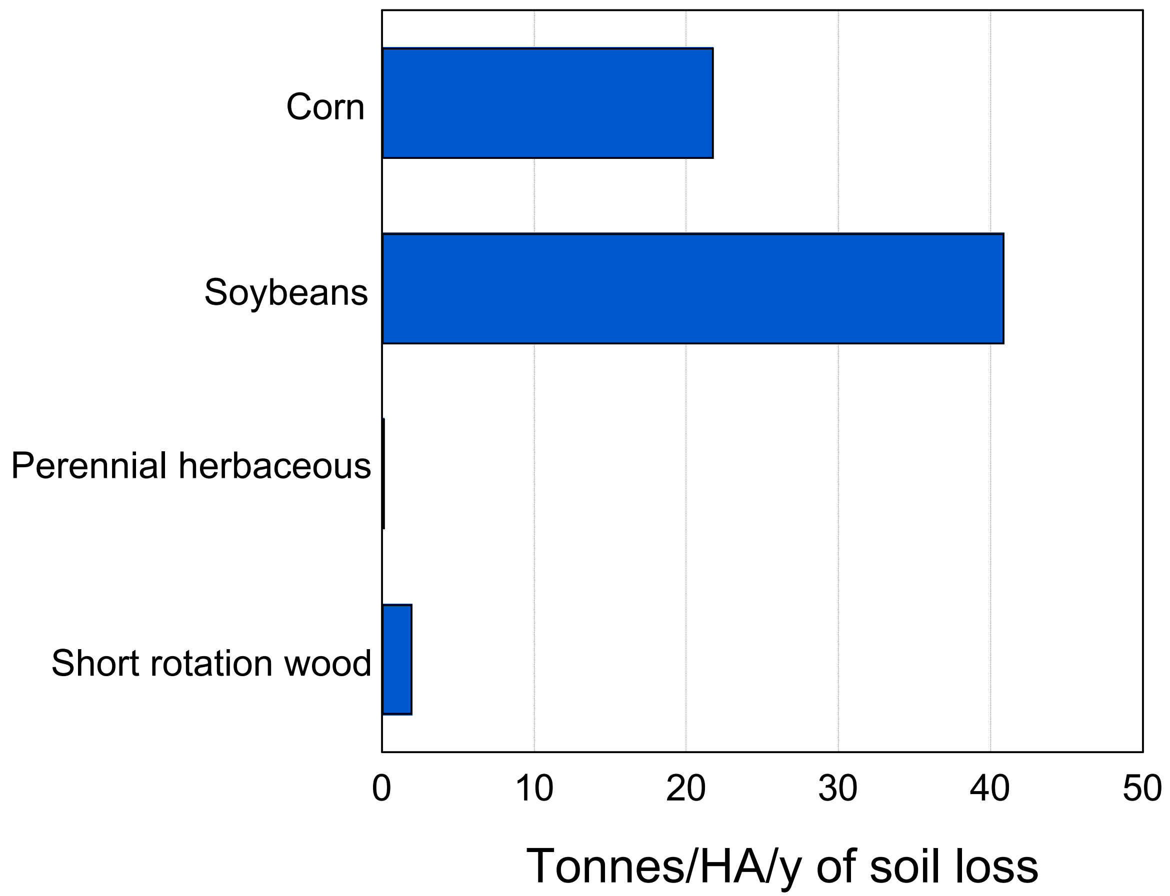
Richard Hamilton, Ceres

Soil carbon increases in perennial crops with all aboveground biomass removed



Tilman, Hill & Lehman Science 314,1598

Perennials have little or no erosion

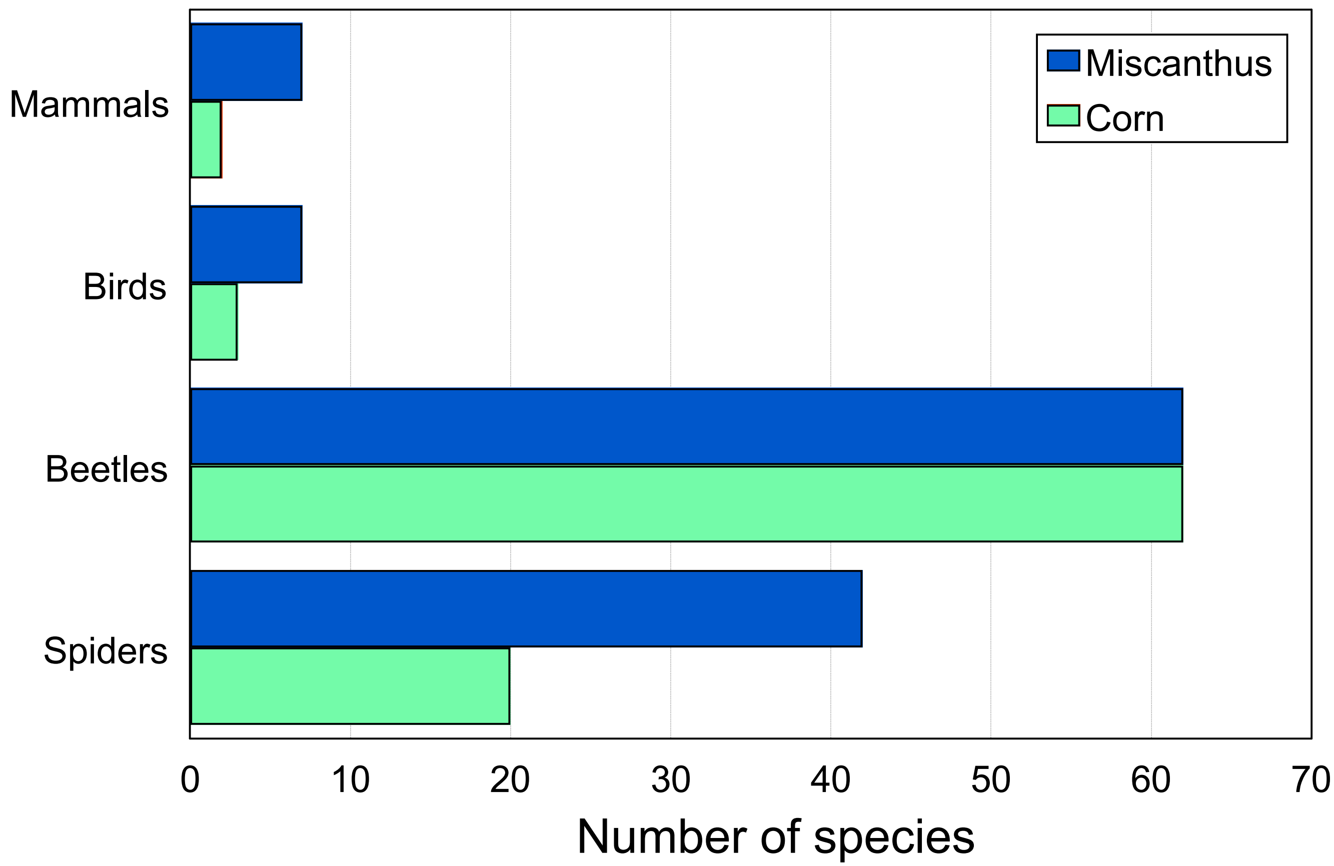


From Oliveira et al in: Jones and Walsh (eds) Miscanthus for Energy and Fibre, 2001

Harvesting Miscanthus

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

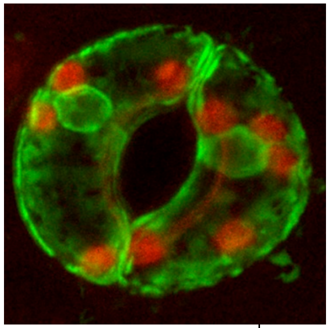
Ecological niches in Miscanthus vs corn in Germany

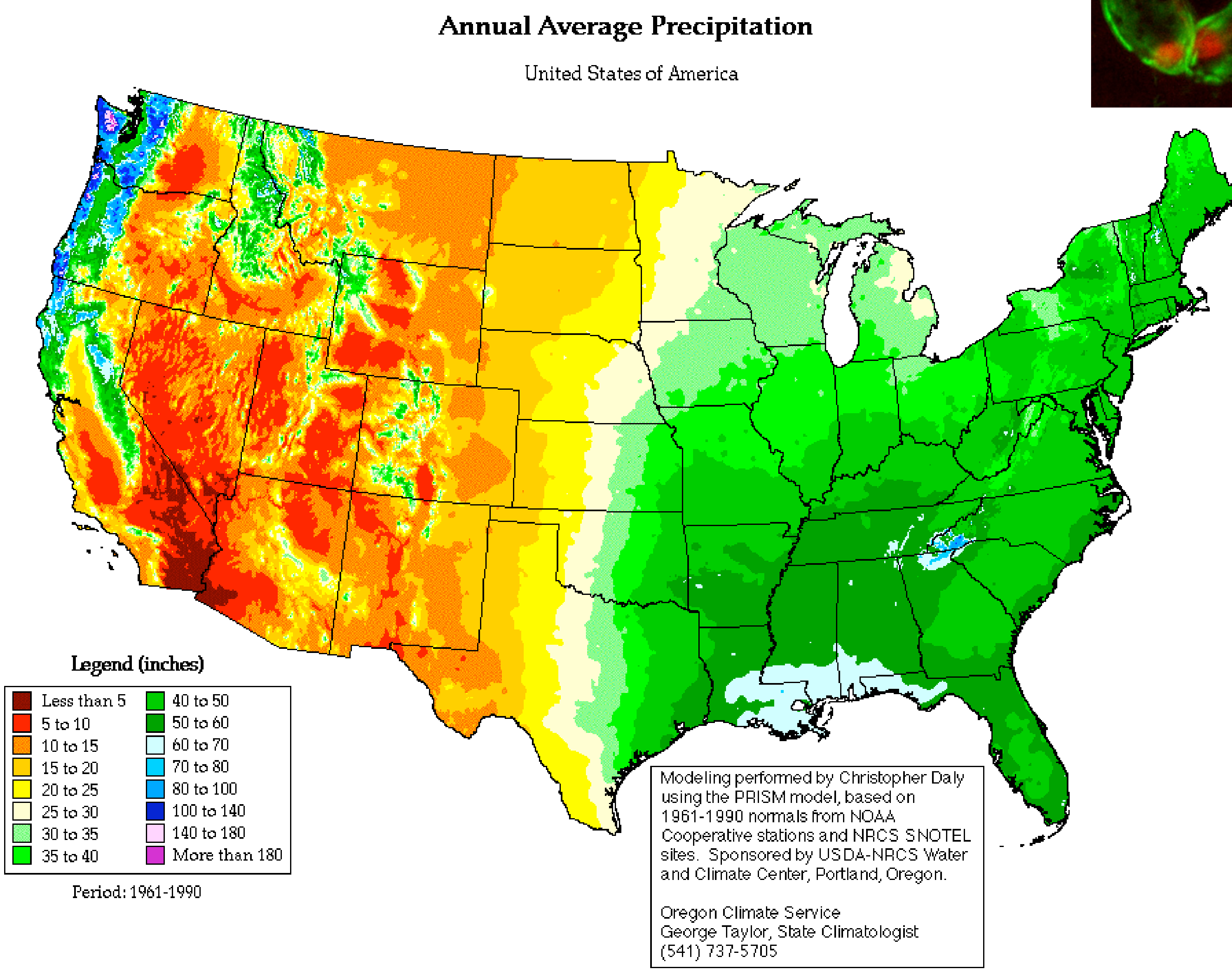


From Oliveira et al in: Jones and Walsh (eds) Miscanthus for Energy and Fibre, 2001

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

Annual precipitation

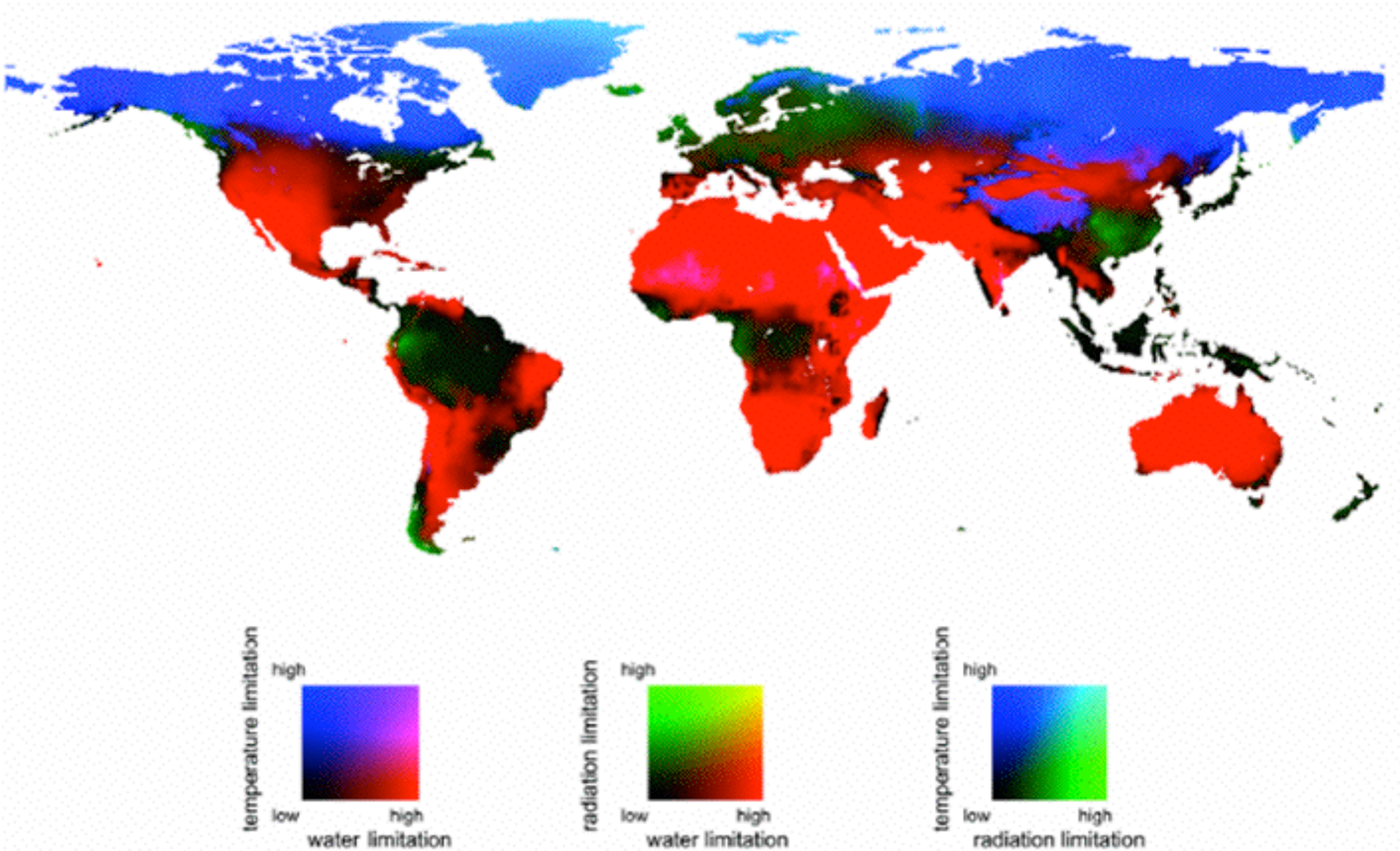




Geographic distribution of biomass

Wright et al DOE-ORNL-EERE

Limiting factors for global NPP



Baldocchi et al. 2004 SCOPE 62

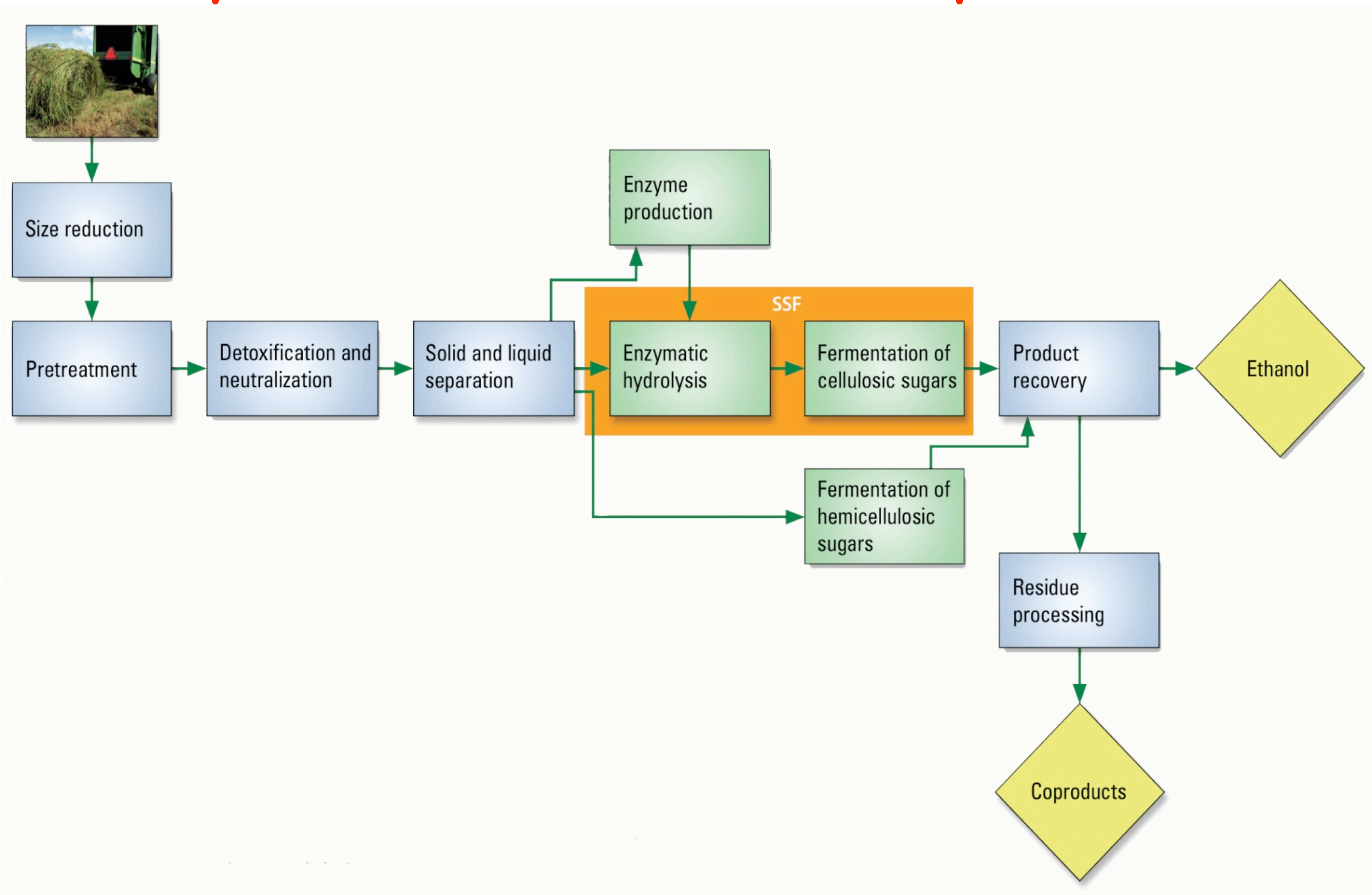
Economics of Perennials are Favorable

CROP	Yield per Acre	Value $	Cost $	Profit $
Corn ($4.2/bu) ($150/t)	160 bu	672	193*	479
Switchgrass ($50/t)	10 tons	500	138**	362
Miscanthus ($50/t)	15 tons	750	138**	612

*USDA economic research service 2004

**50% as much fertilizer, no chemicals

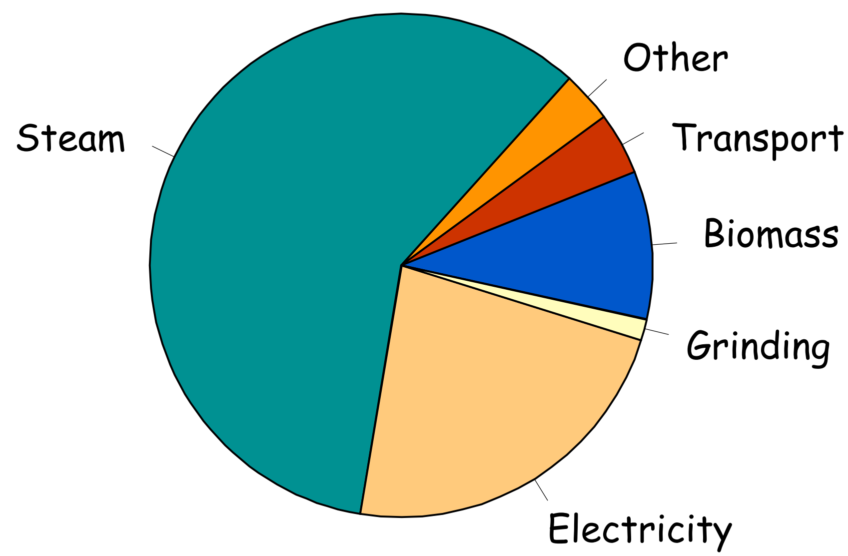
Steps in cellulosic ethanol production



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

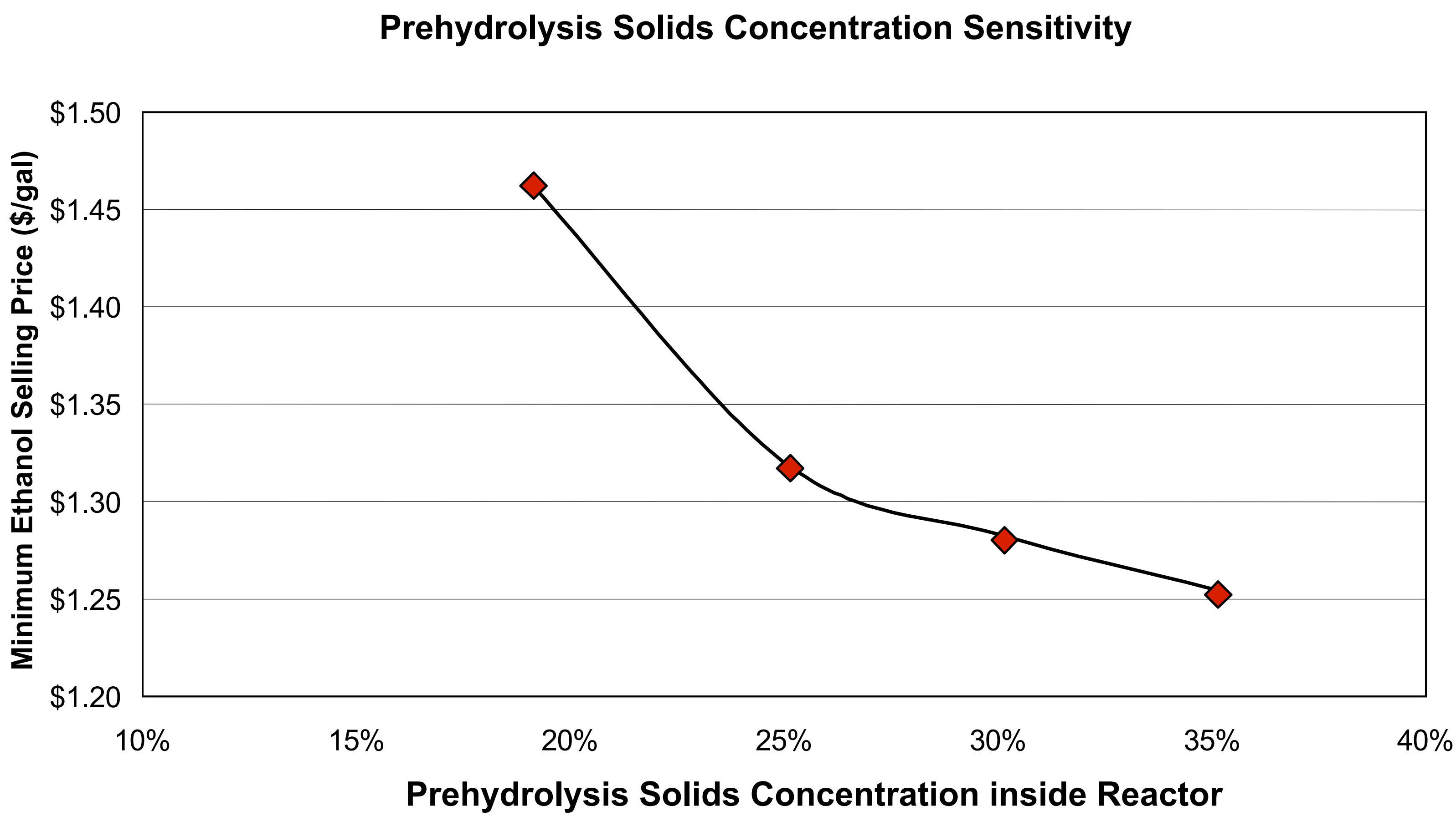


Energy consumption

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

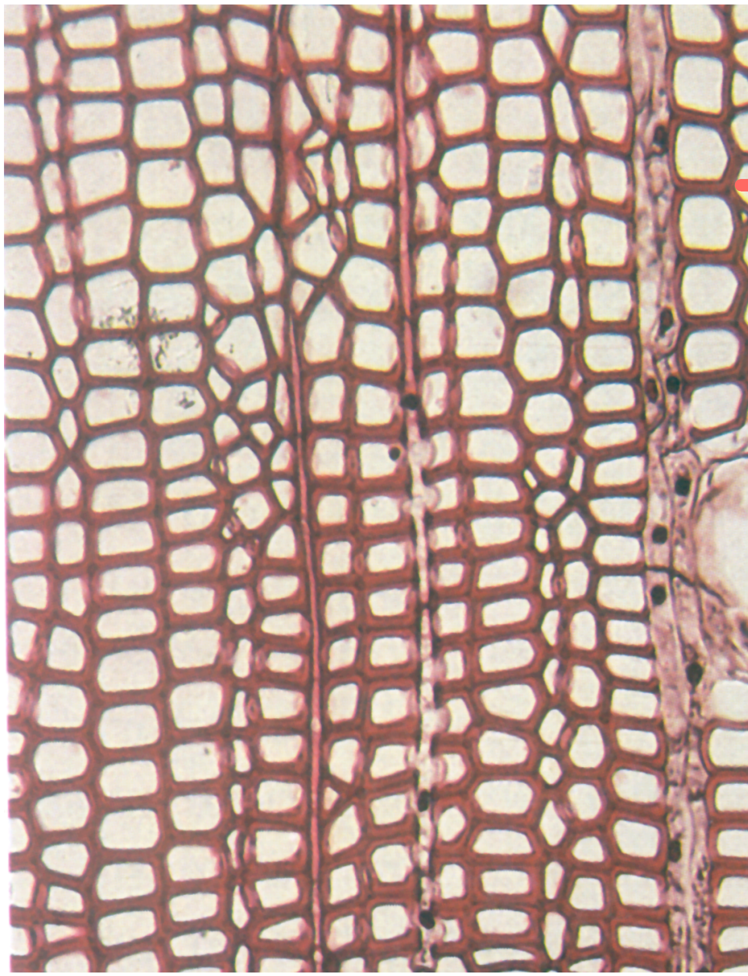
Pretreatment - Example

Reactor Solids Cost Impact:

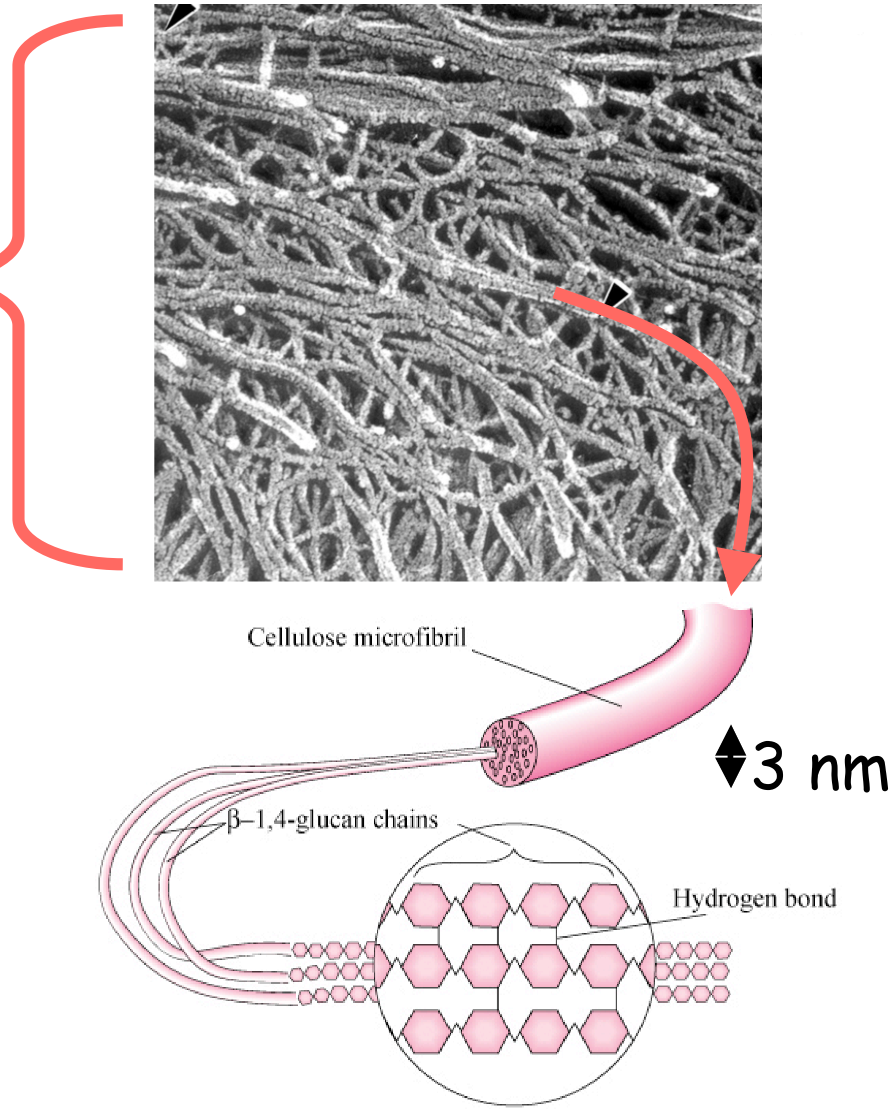


NREL Analysis

Plants are mostly composed of sugars

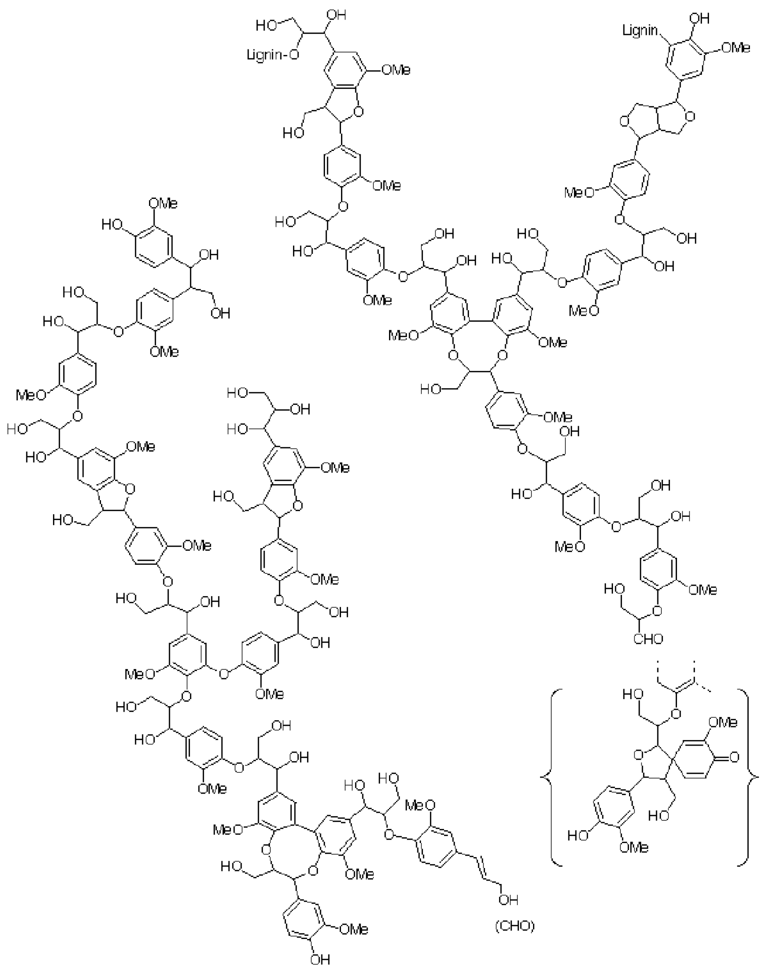


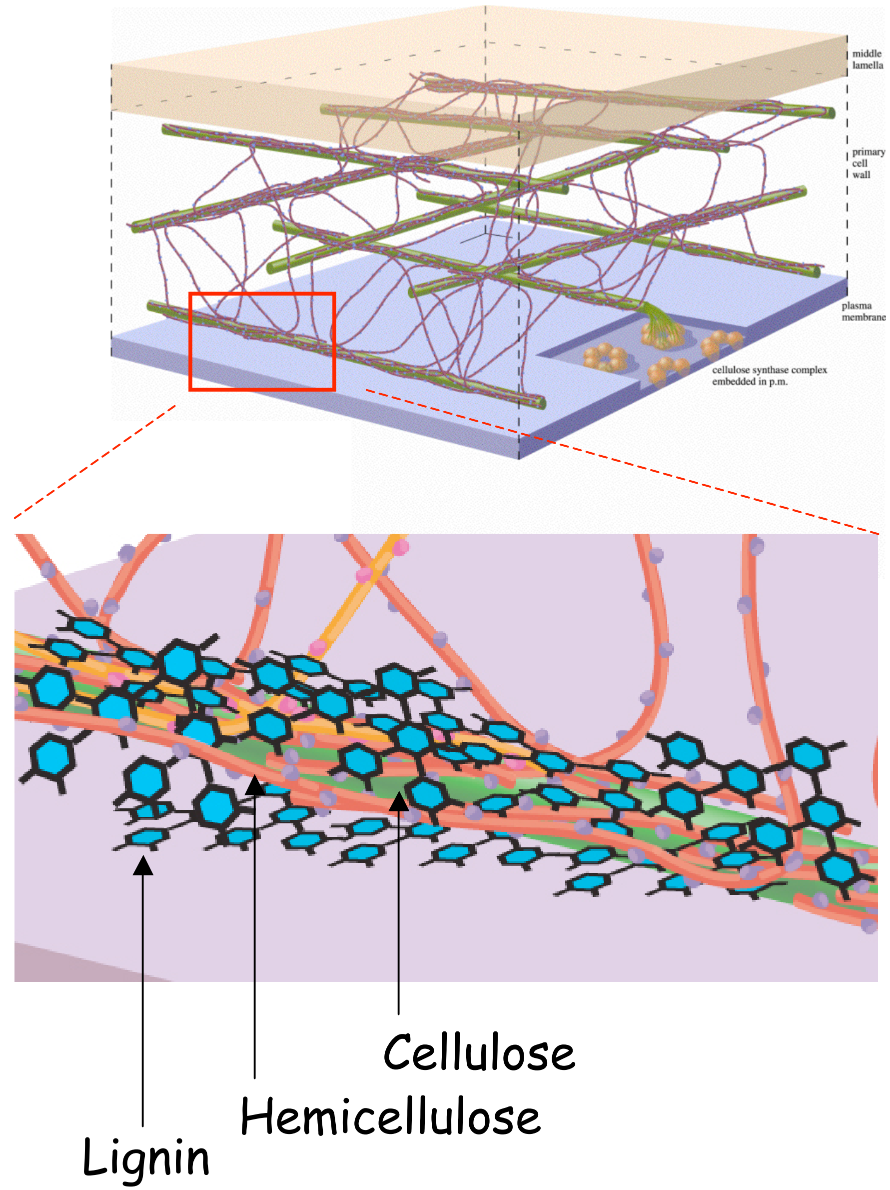
Section of a pine board



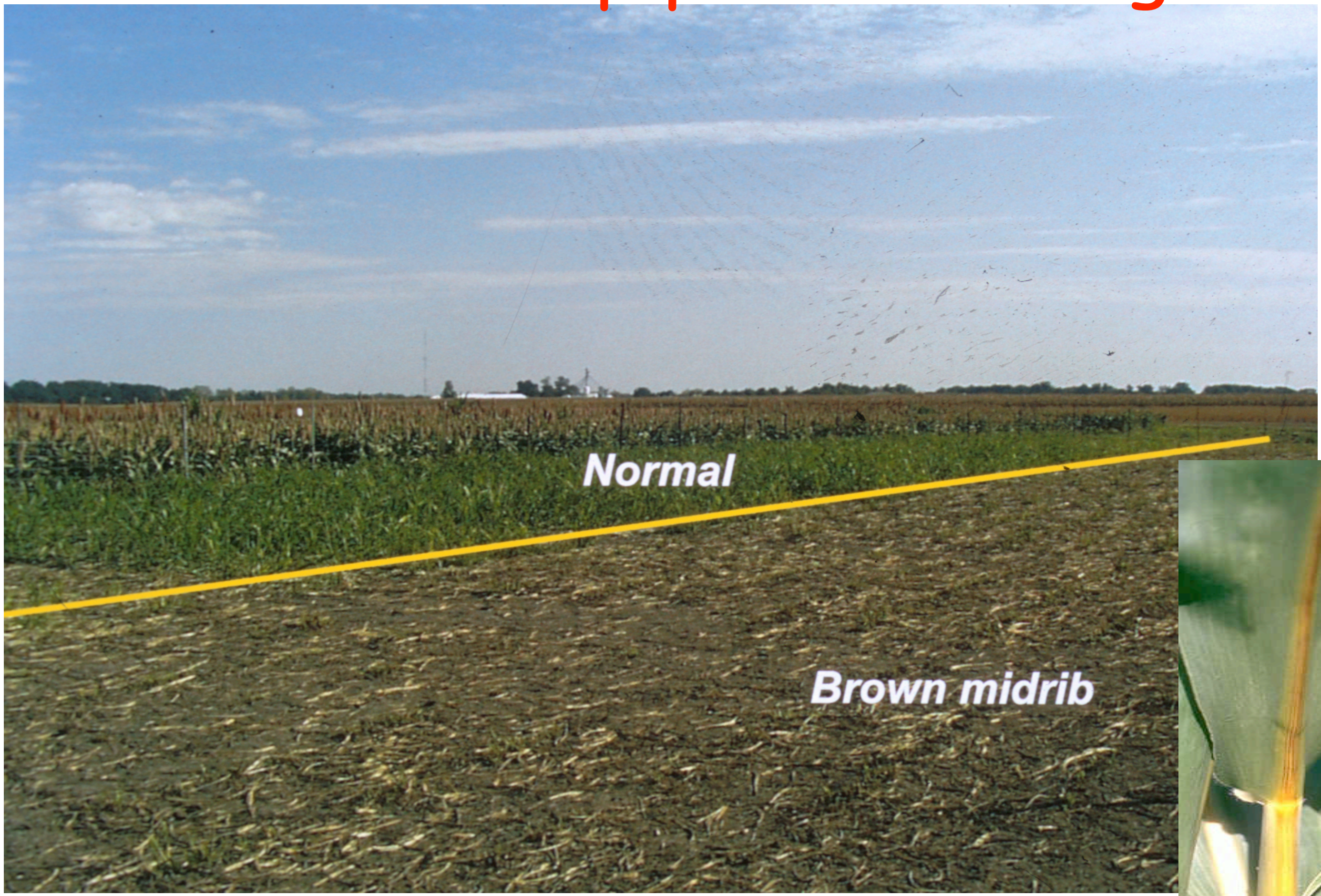
Polymerized glucose

Lignin occludes polysaccharides



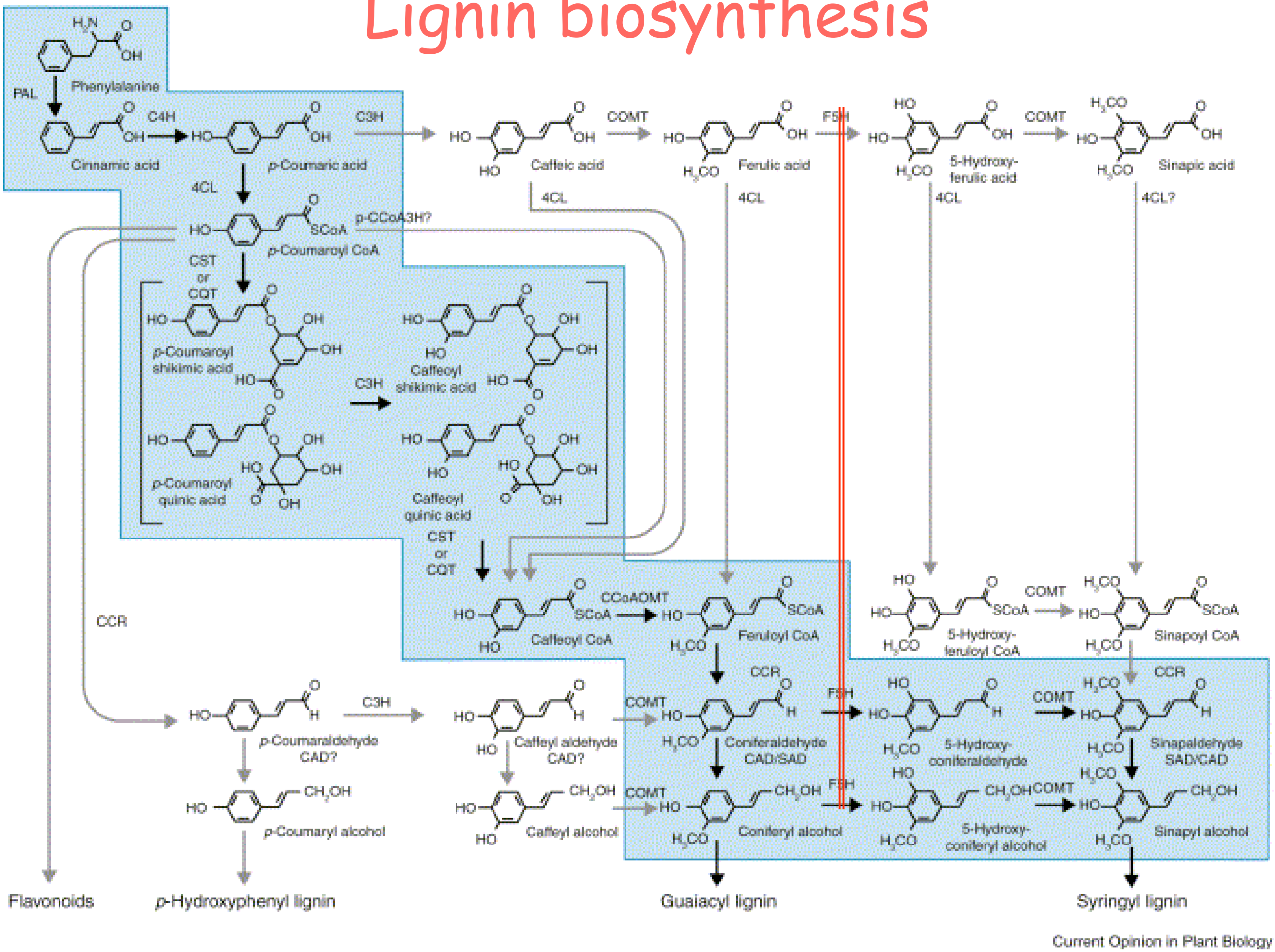


Sheep prefer low lignin



Clint Chapple, Purdue

Lignin biosynthesis

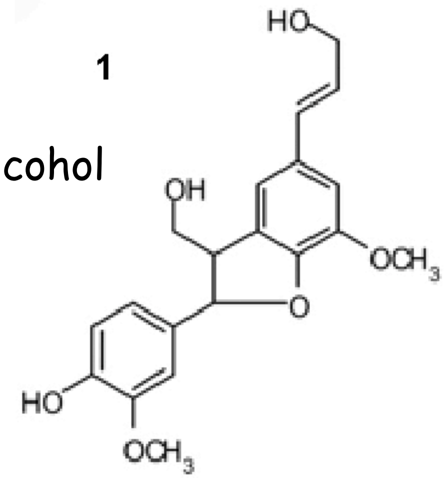


Humphreys and Chapple, Curr Opin Plant Biol 5,224

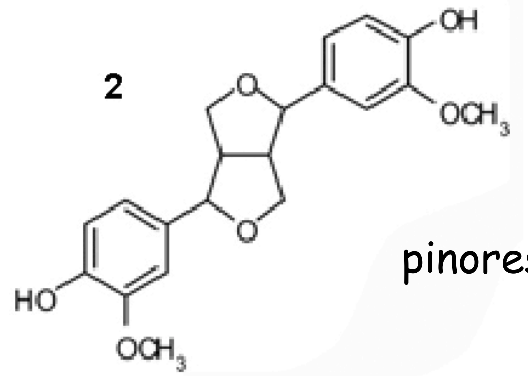
A cleavable lignin precursor would fundamentally alter preprocessing

1

dehydrodiconiferyl alcohol

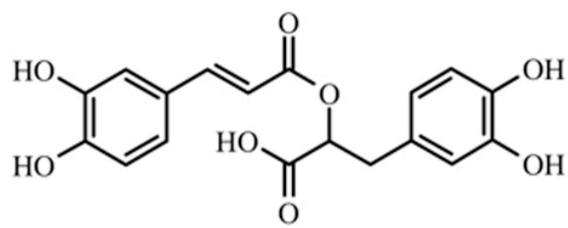


2



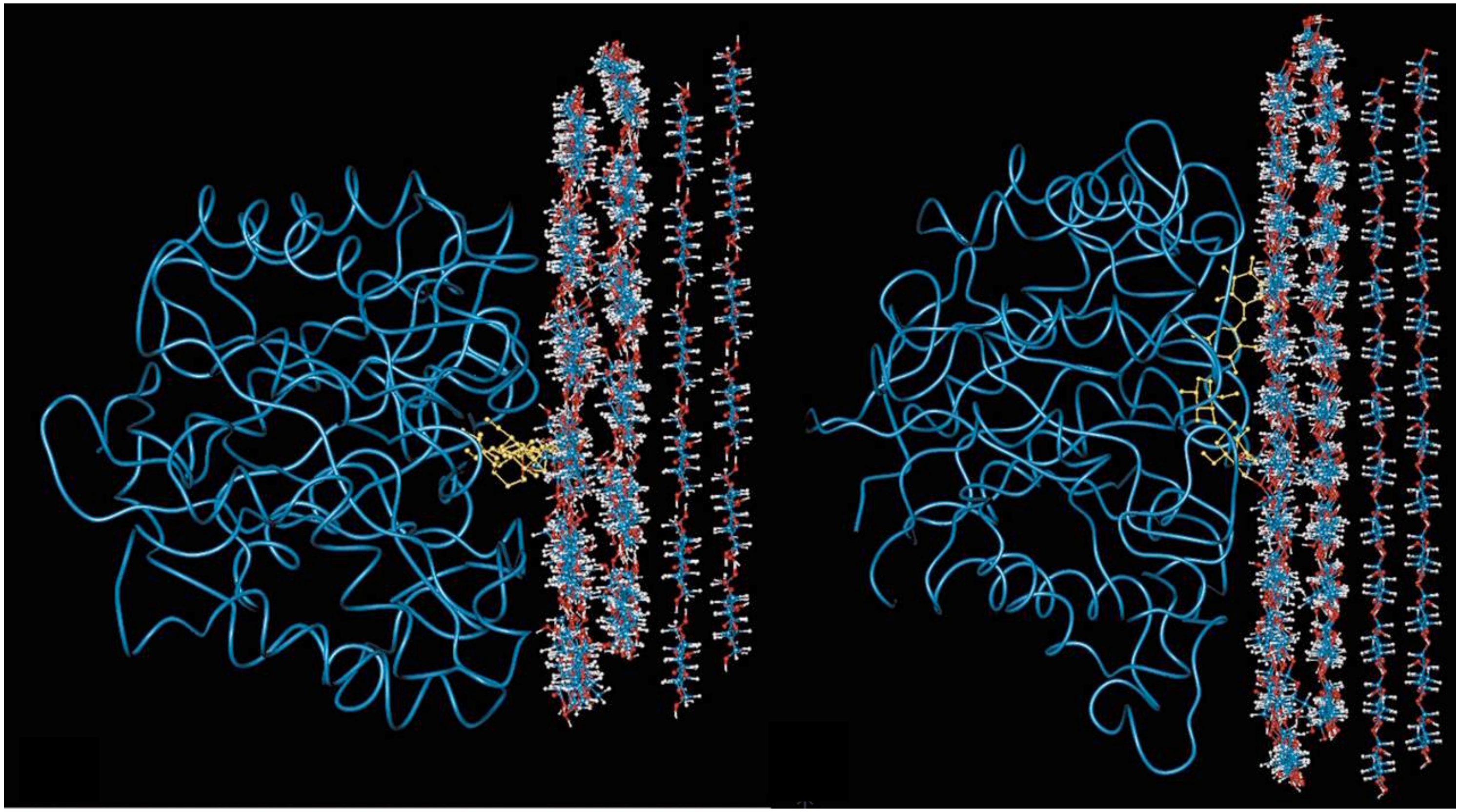
pinoresinol

3



rosmarinic acid

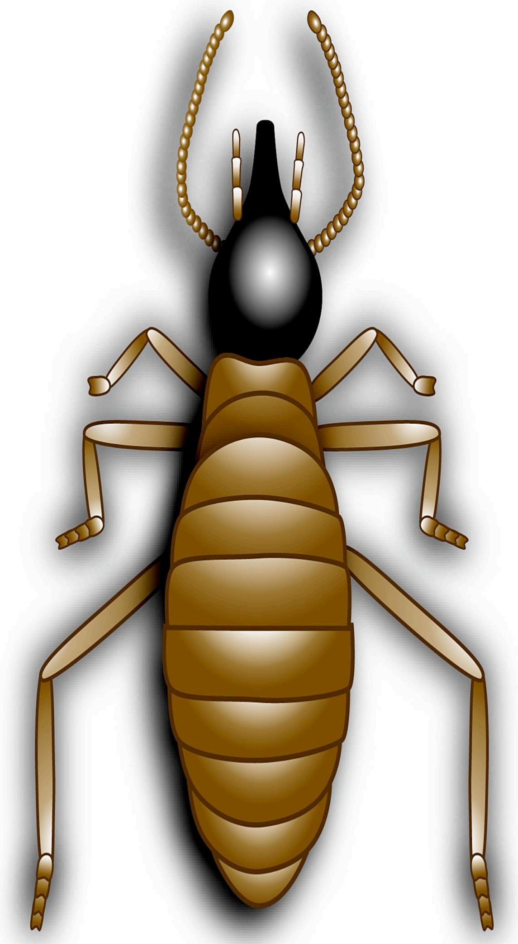
Enzymatic hydrolysis of cellulose is slow



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

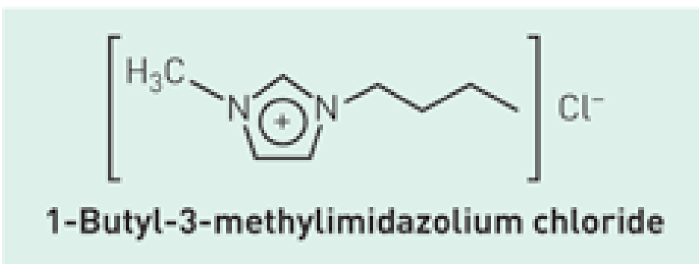
Possible routes to improved catalysts

- 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)

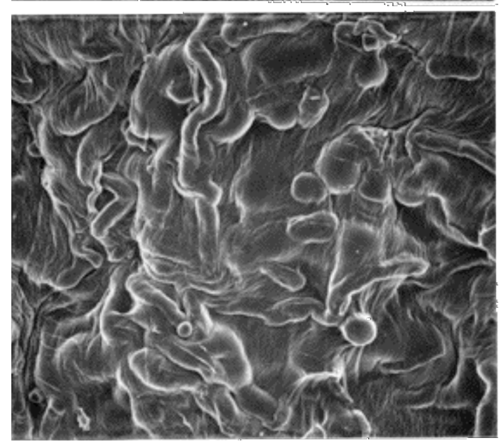


Dissolution of cellulose in an ionic liquid

(novel pretreatment methods may create fundamental changes)



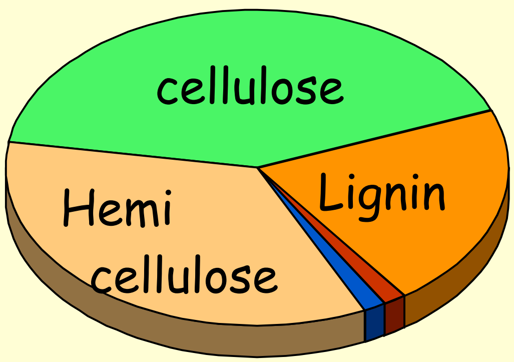
Untreated



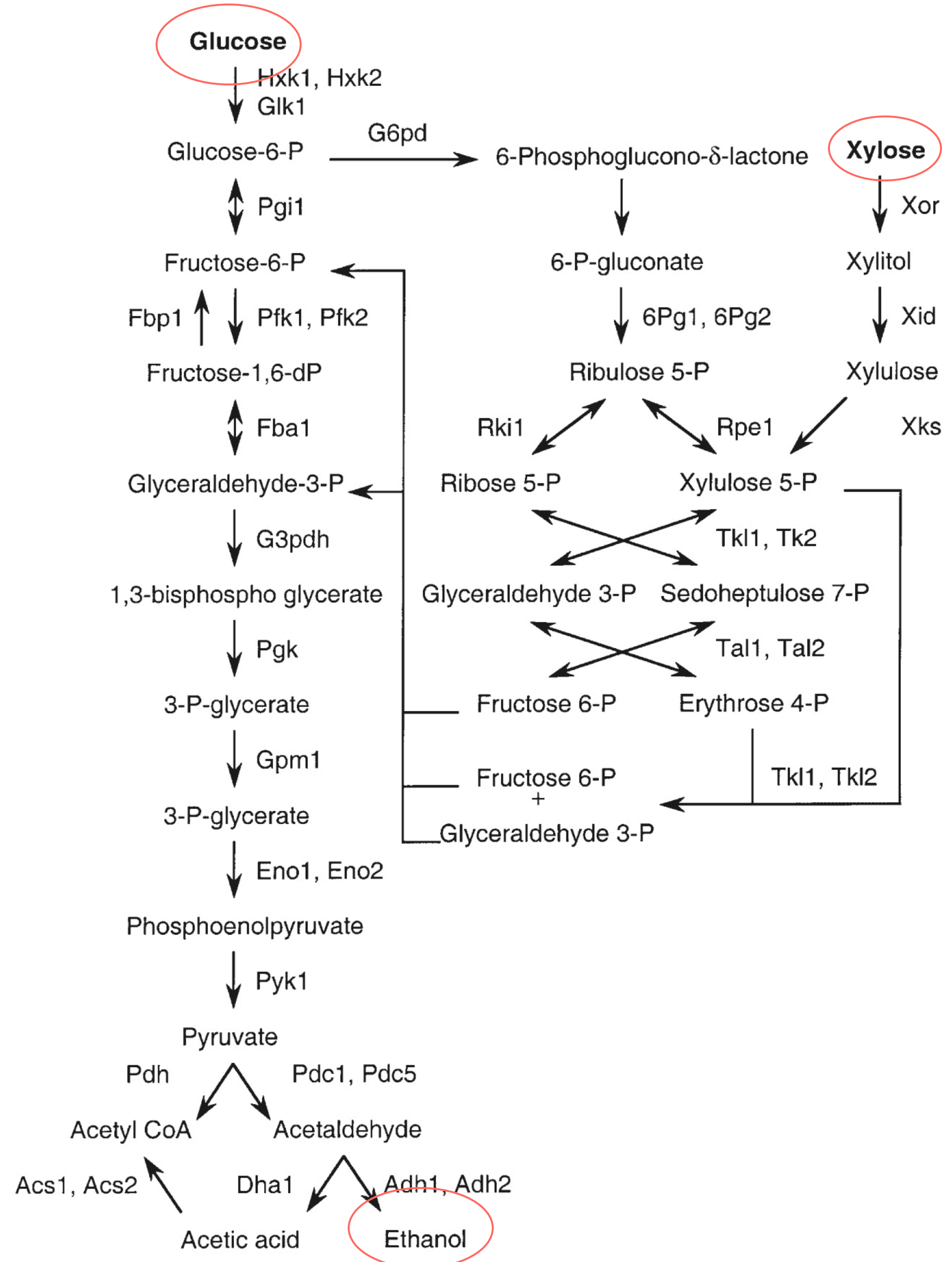
Treated

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

Fermentation of all sugars is essential

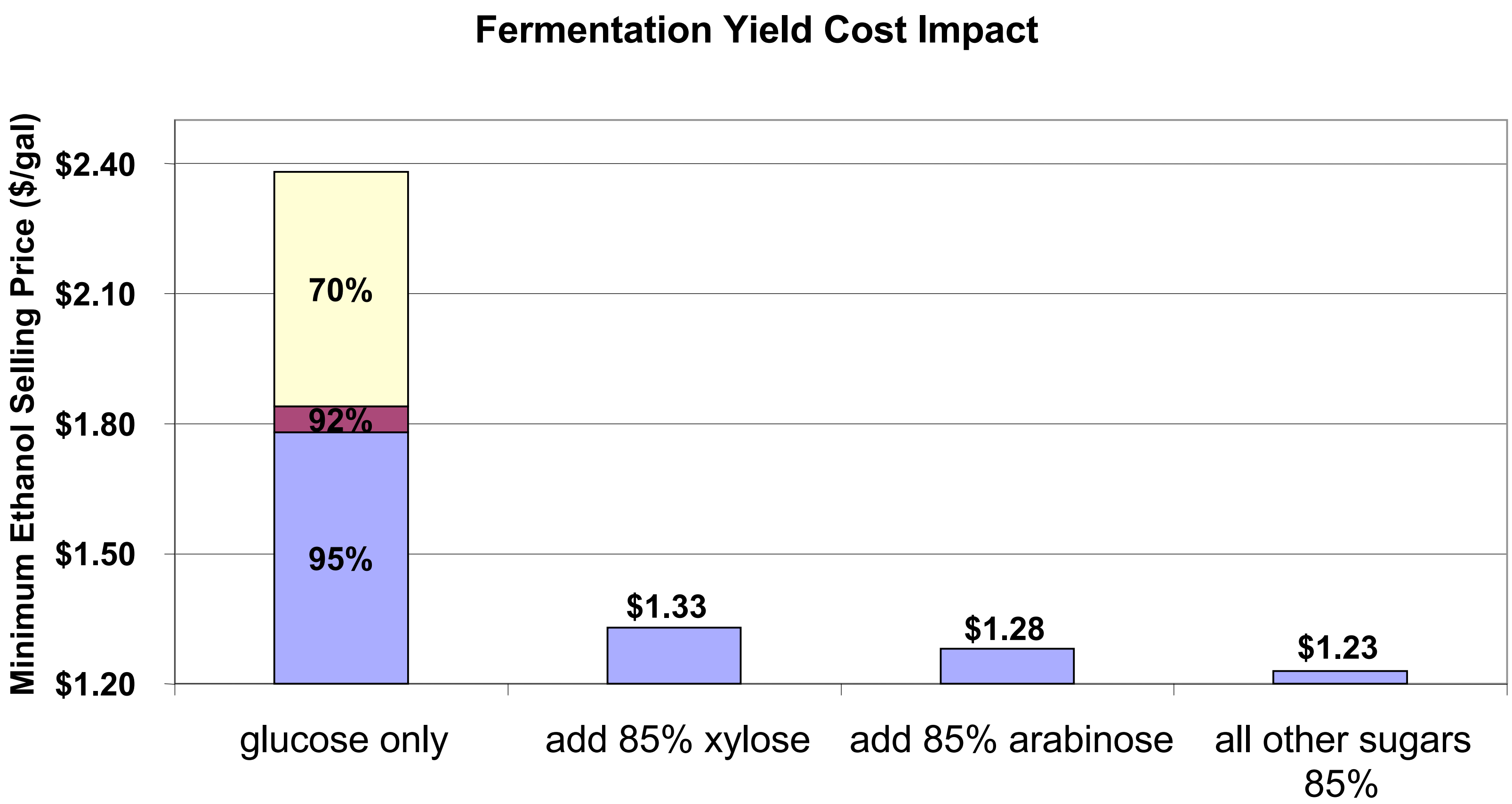


Typical grass composition



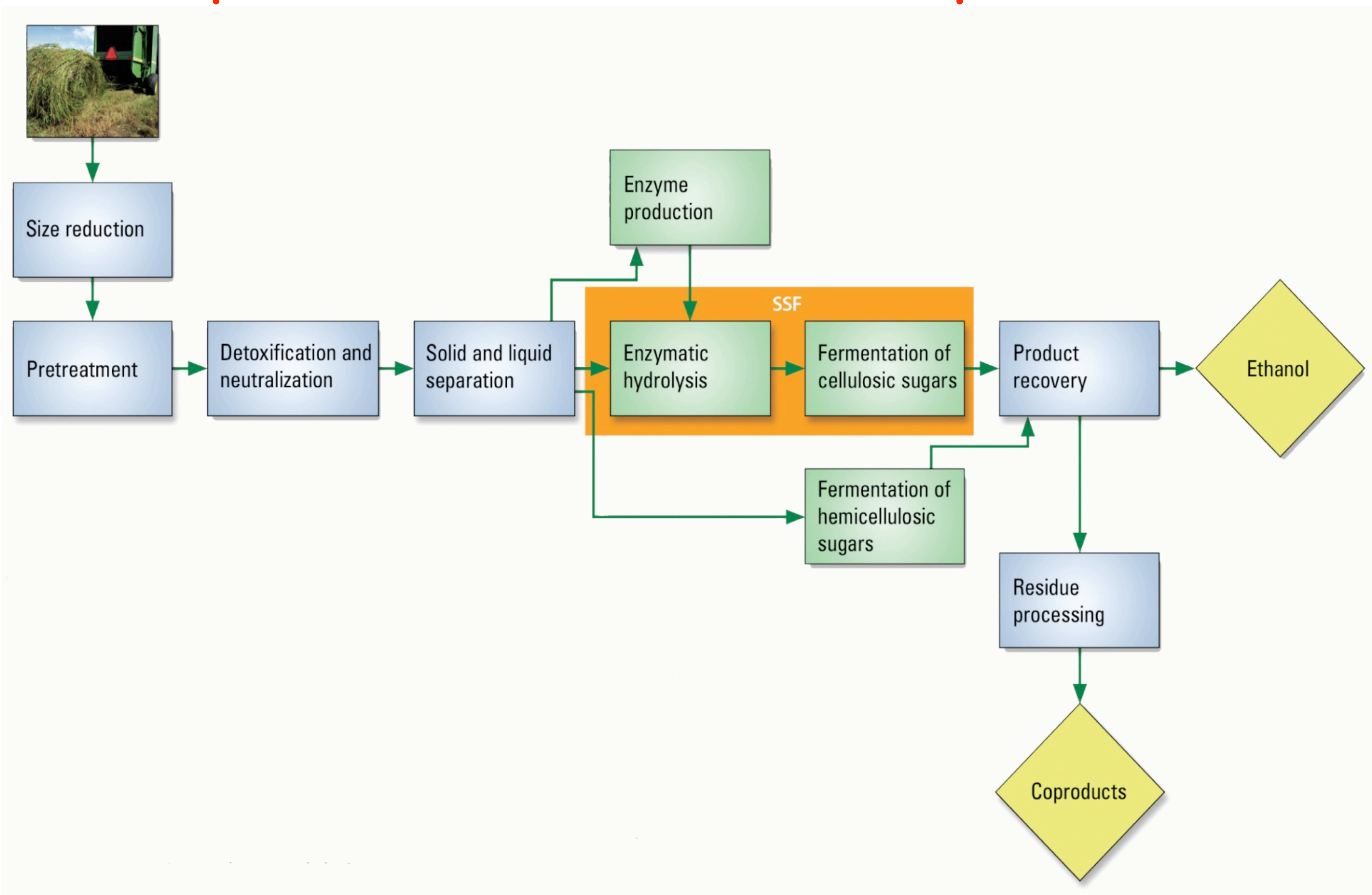
Jeffries & Shi Adv Bioch Eng 65,118

Saccharification & Fermentation



NREL

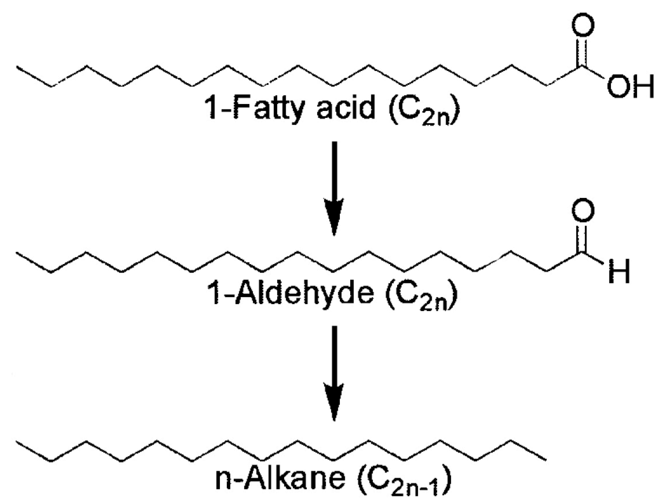
Steps in cellulosic ethanol production



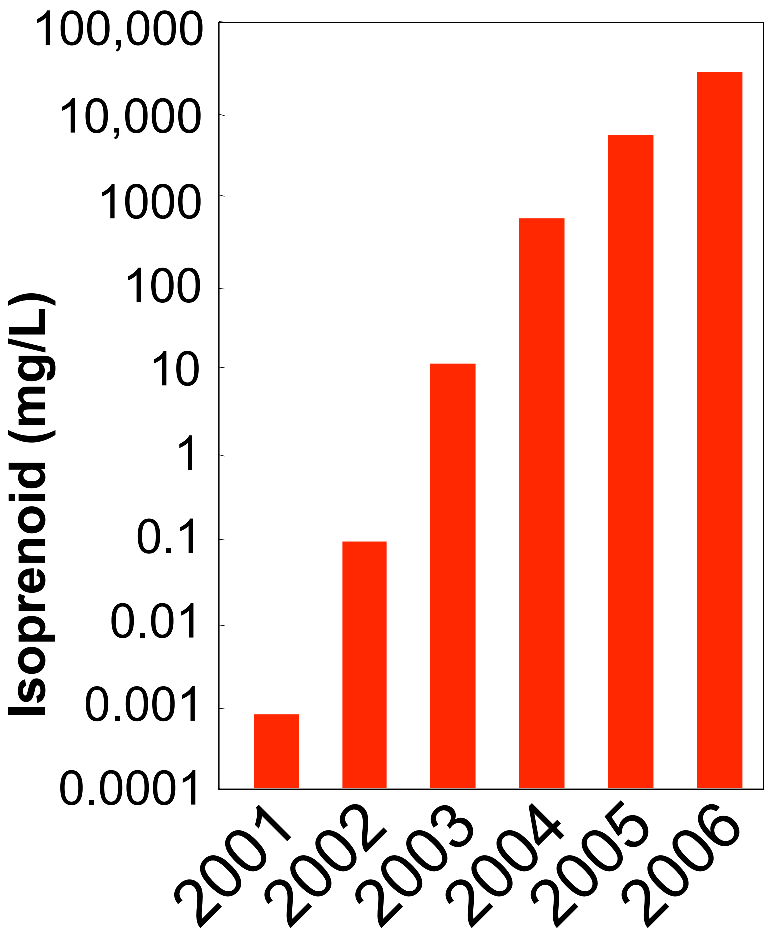
From: Breaking the Biological Barriers to Cellulosic Ethanol

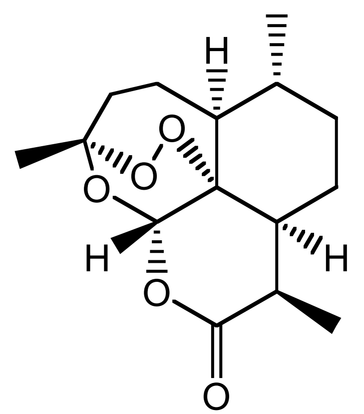
Nature offers many alternatives to ethanol

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



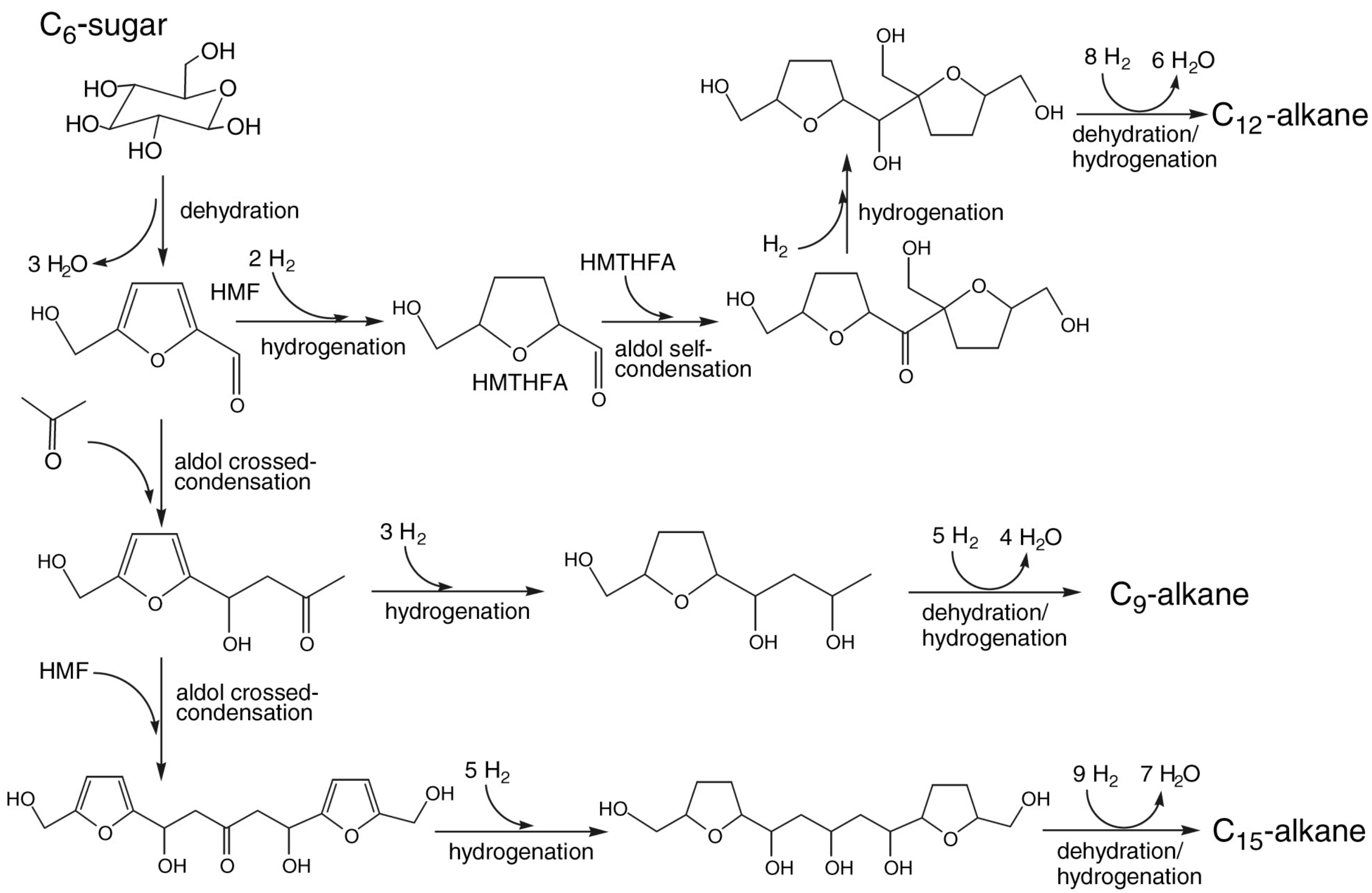
Microbial synthesis of artemisinin





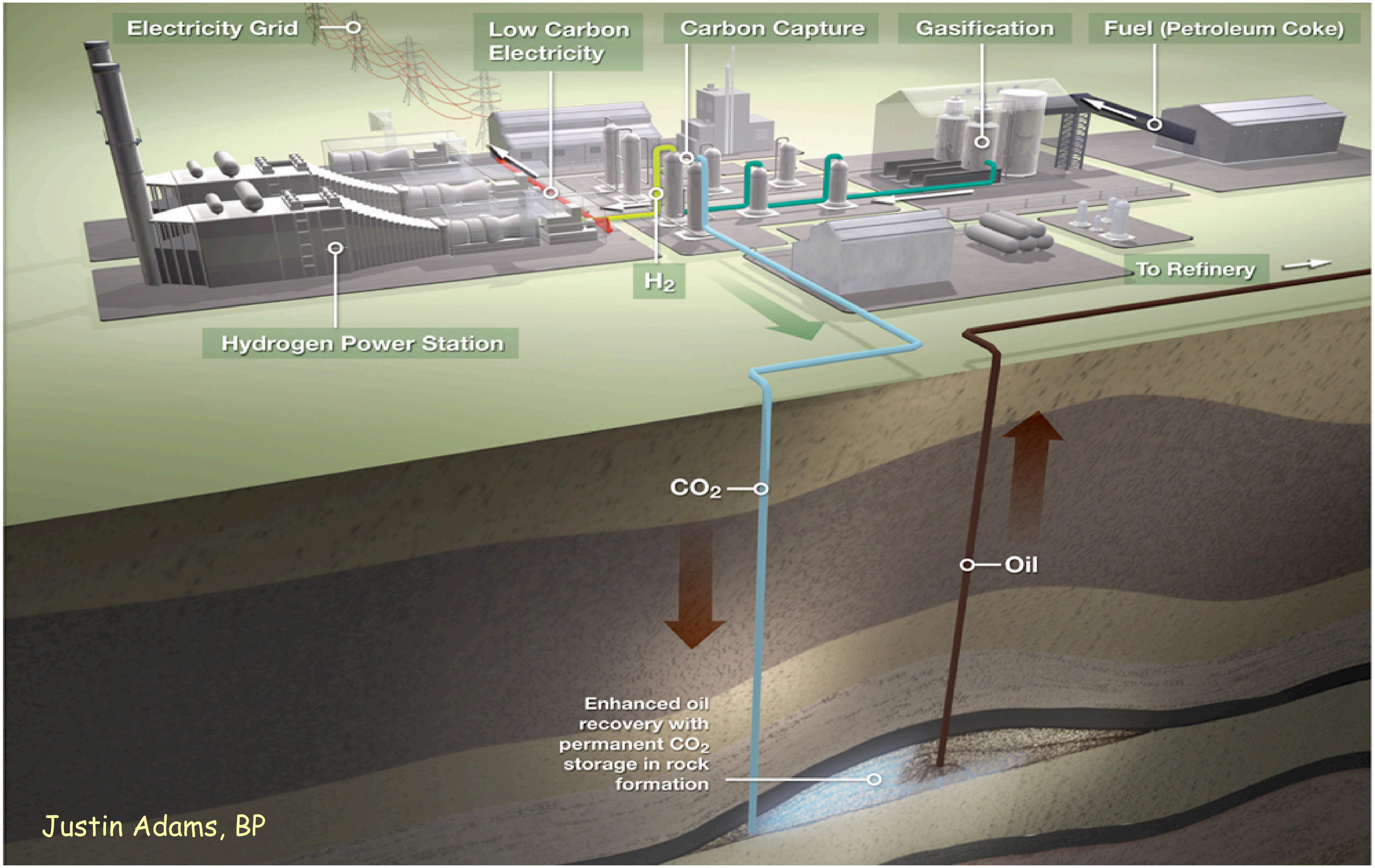
Jay Keasling

Conversion of sugar to alkanes



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

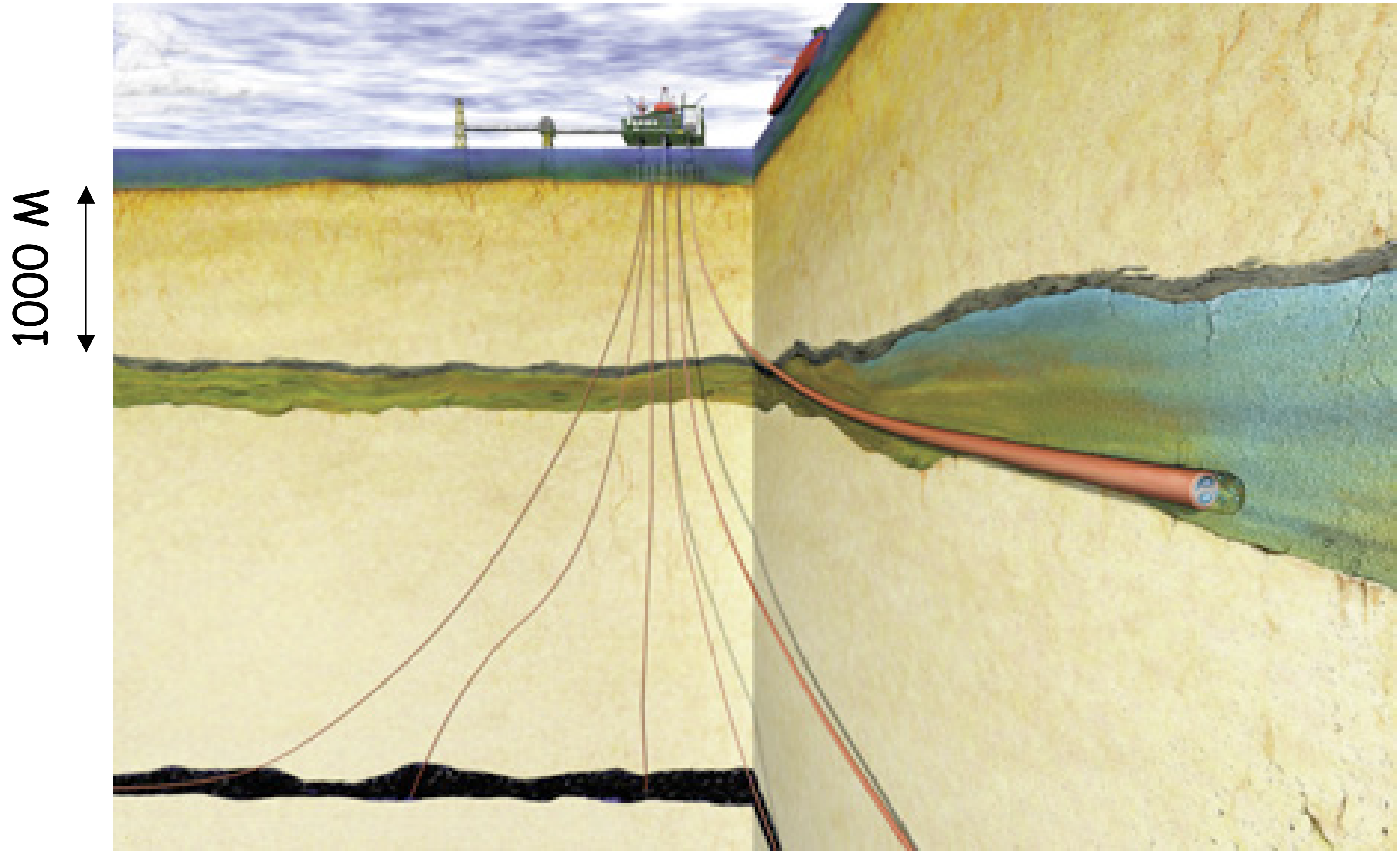
The “hydrogen economy”



The Sleipner Experiment

1 million tons/y; capacity 600 B tons

7000 such sites needed

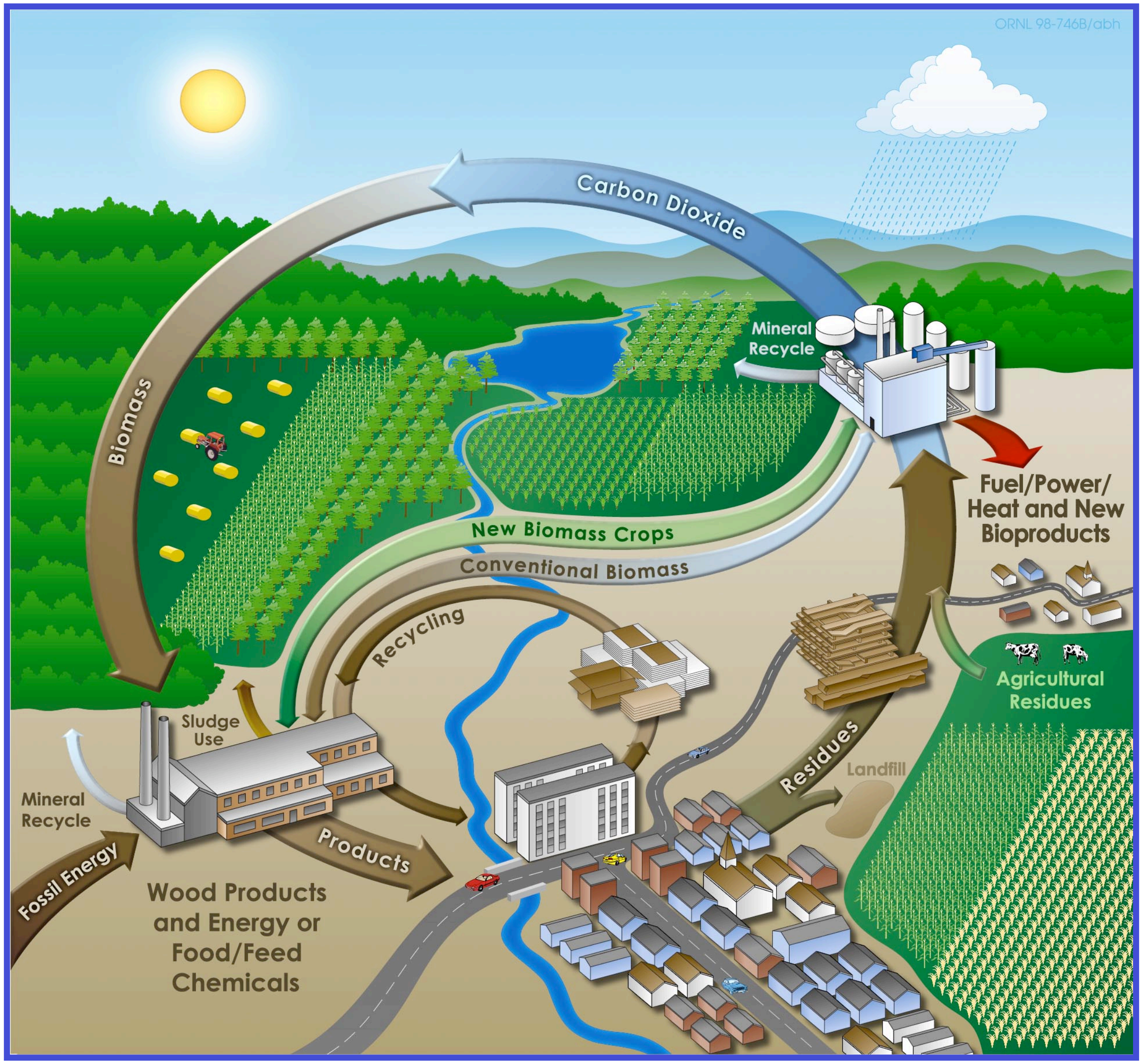


www.agiweb.org/geotimes

Summary of priorities

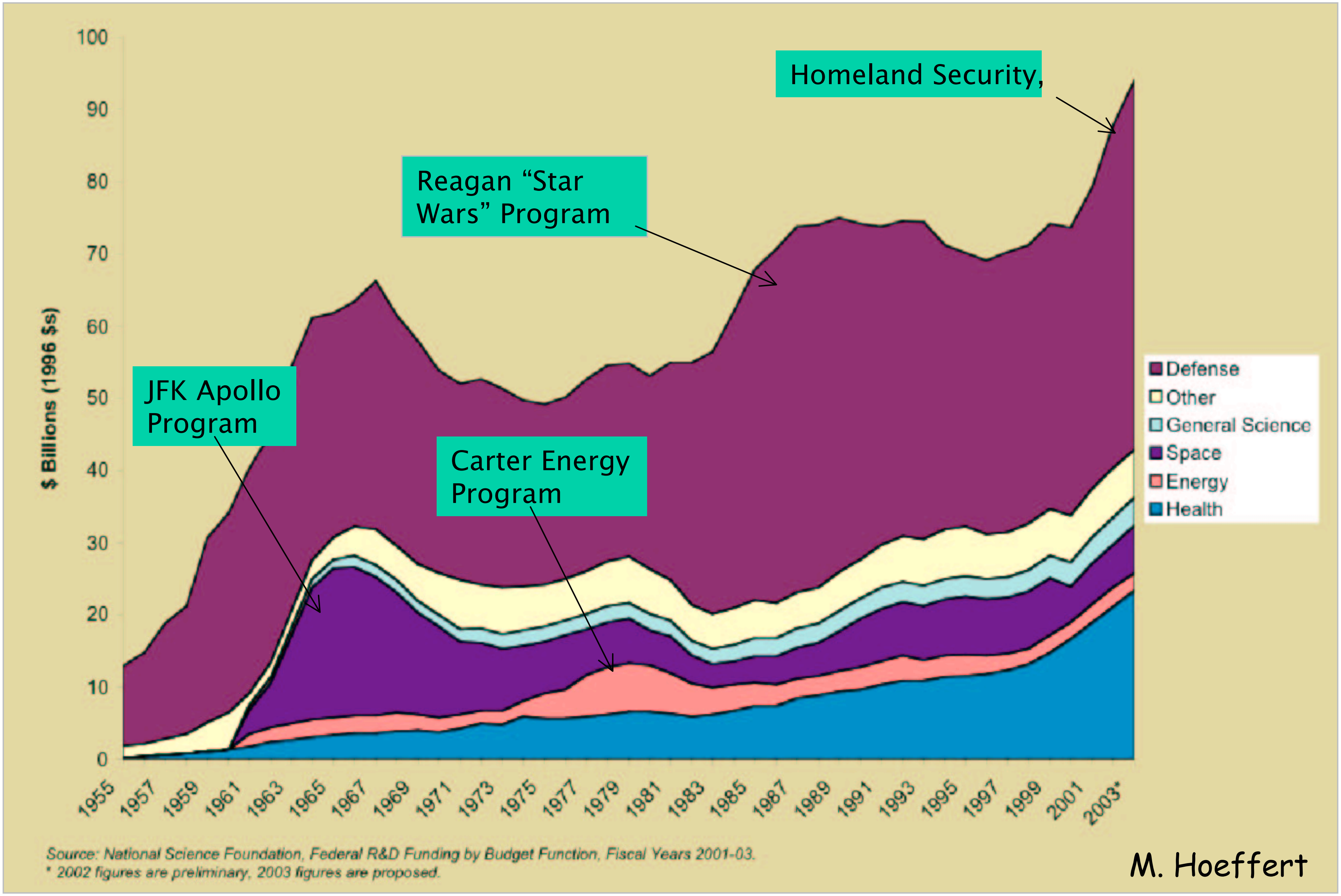
- Develop energy crops and associated agronomic practices
- Identify or create more active catalysts for conversion of biomass to sugars
- Develop industrial microorganisms that ferment all sugars
- Develop new types of microorganisms that produce and secrete hydrophobic compounds

A vision of the Future

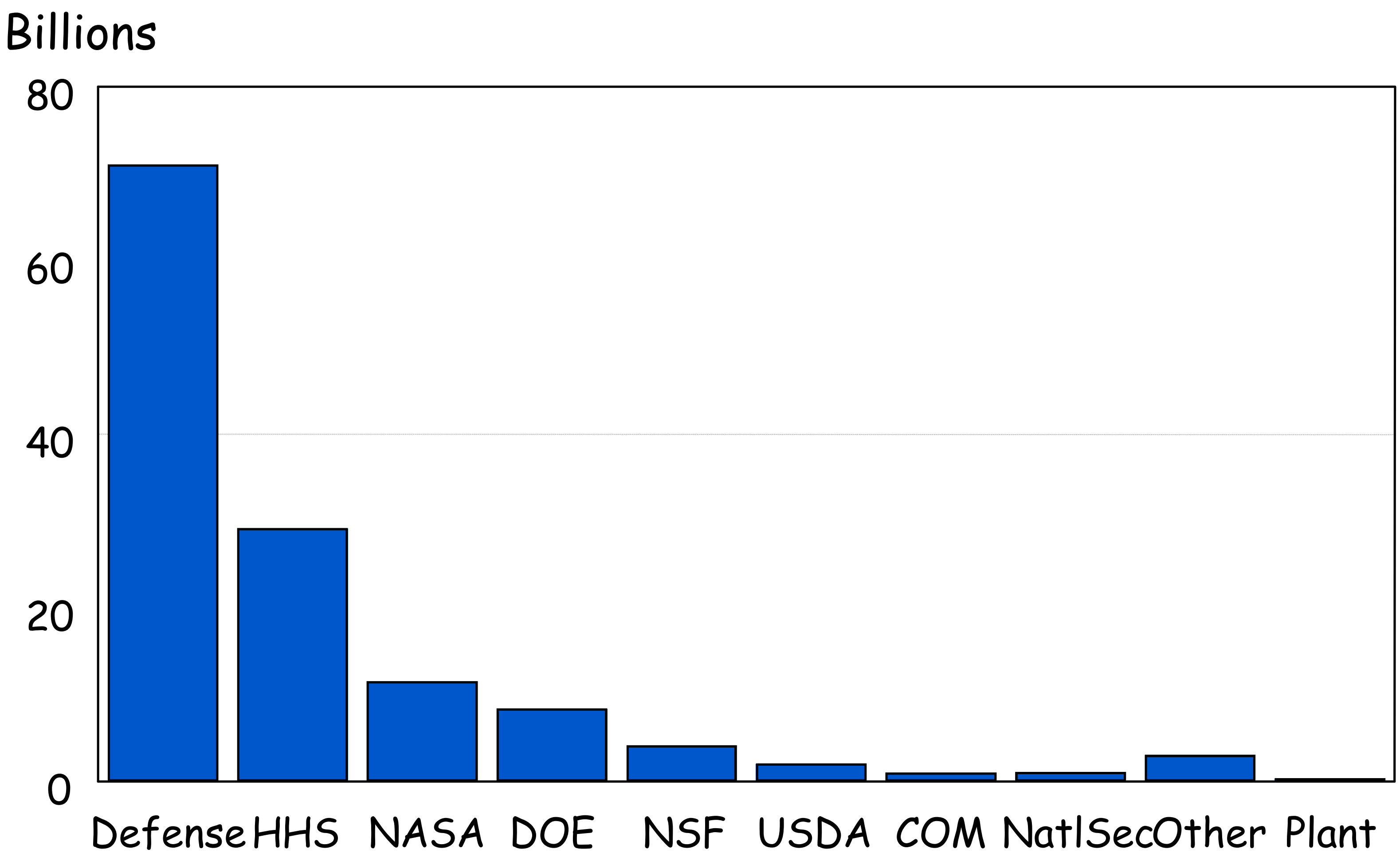


http://genomicsgtl.energy.gov/biofuels/index.shtml

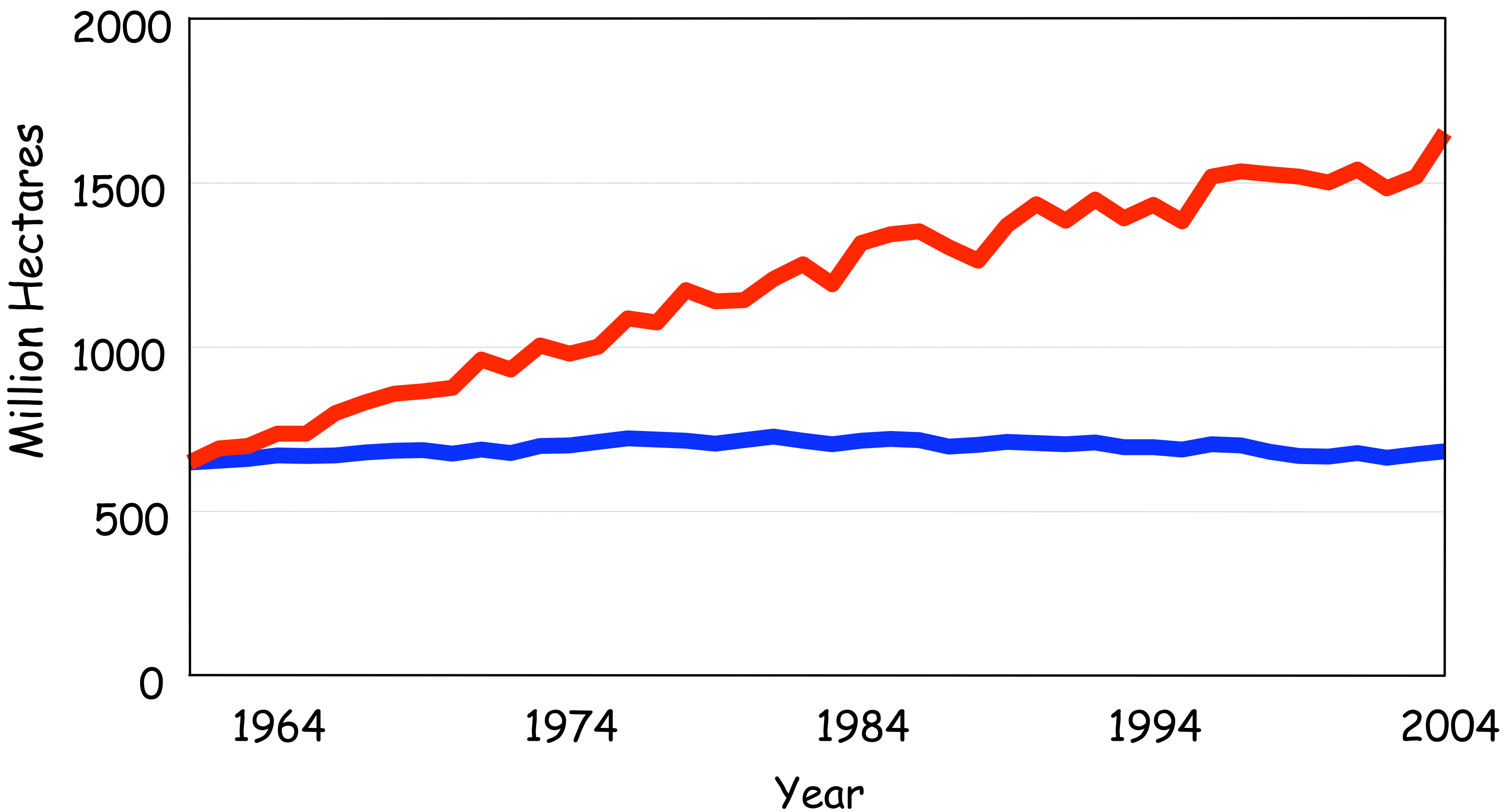
HISTORY OF US FEDERAL GOVERNMENT R & D



Federal Research Budget 2006

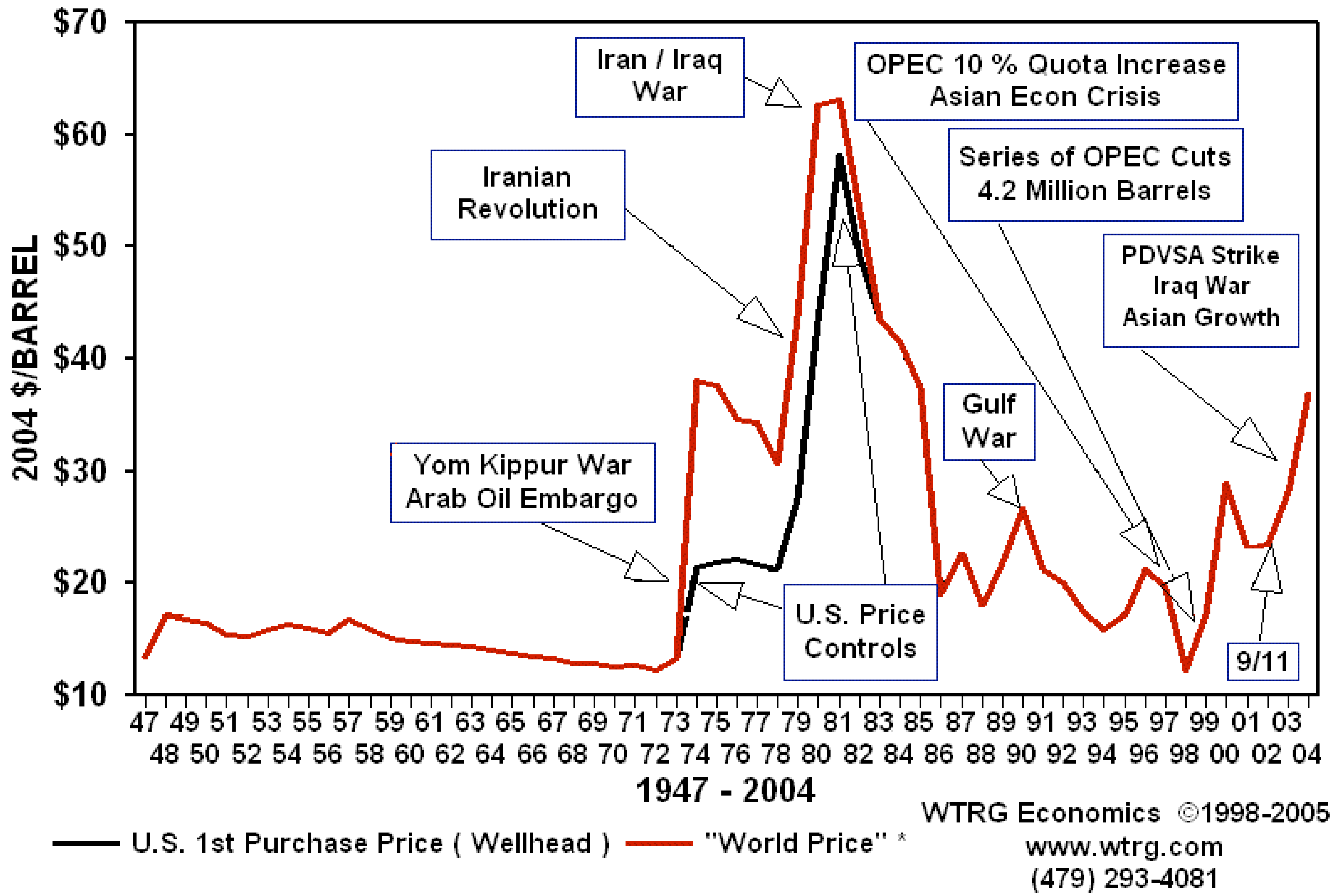


Global grain production with and without yield enhancements

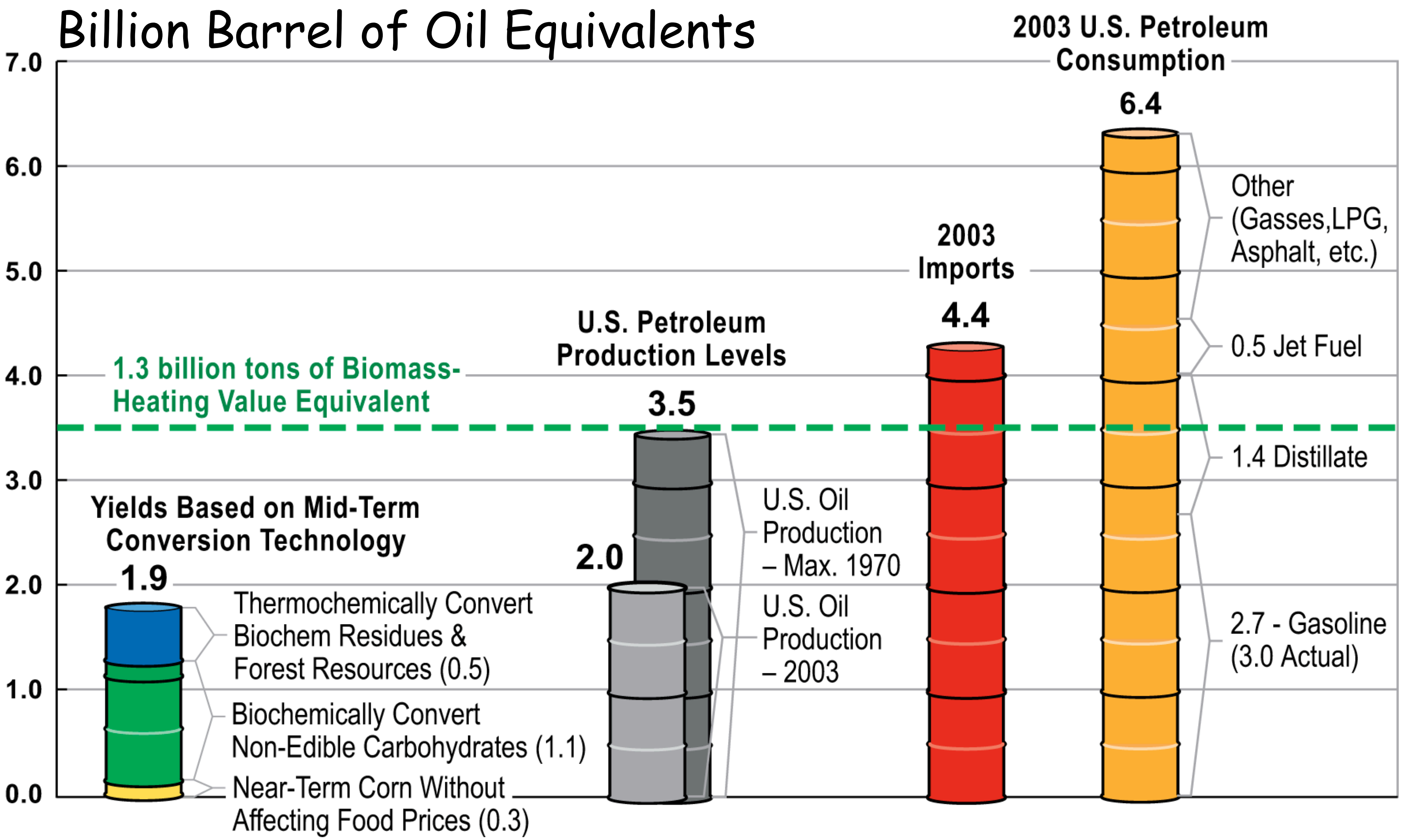


Data from worldwatch

Risks: Historical Price of Oil



The 1.3 Billion Ton Biomass Scenario



Based on ORNL & USDA Resource Assessment Study by Perlach et.al. (April 2005)
http://www.eere.energy.gov/biomass/pdfs/final_billionton_vision_report2.pdf