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Agricultural Outlook Forum  
U.S. Department of Agriculture

Presented: March 1-2, 2007

## DEVELOPMENT OF CELLULOSIC BIOFUELS

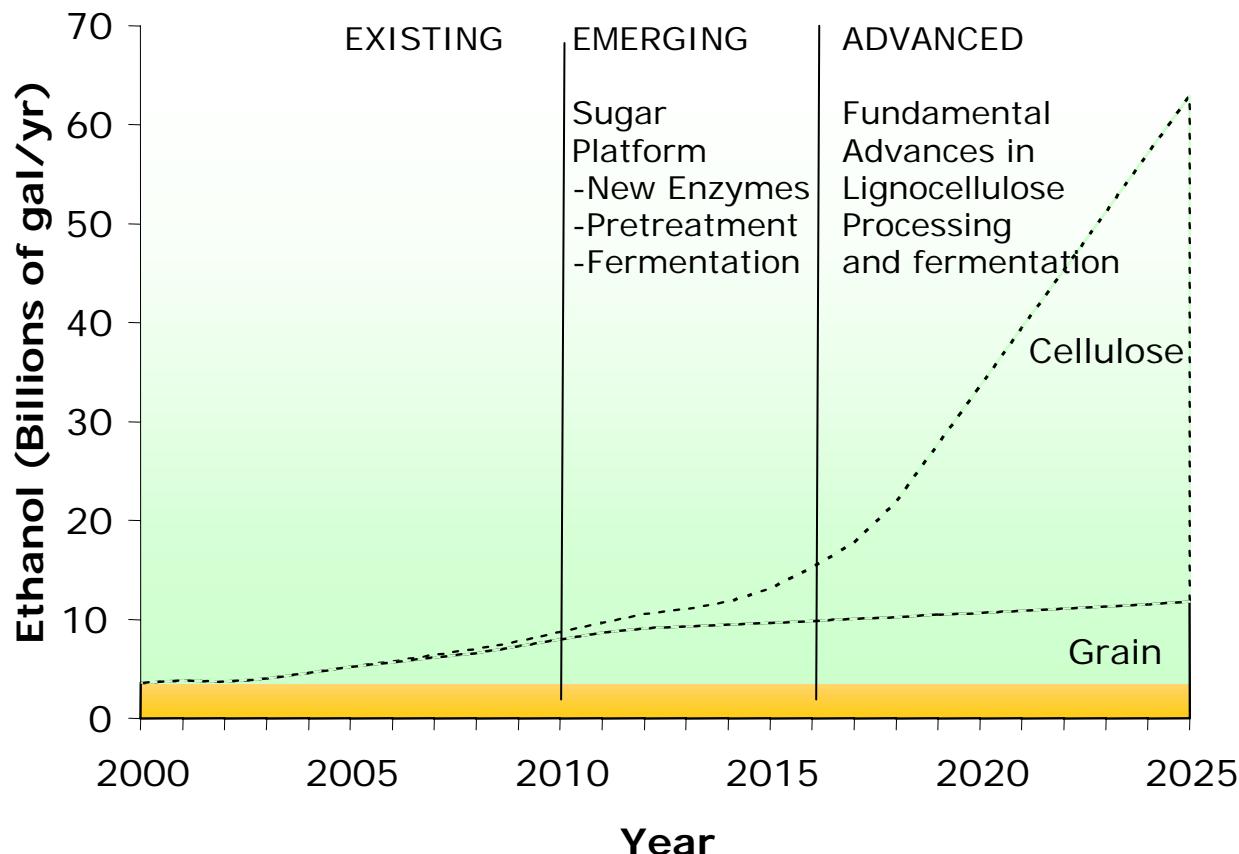
Chris Somerville  
Carnegie Institution, Stanford University  
Lawrence Berkeley National Lab

# Development of Cellulosic Biofuels

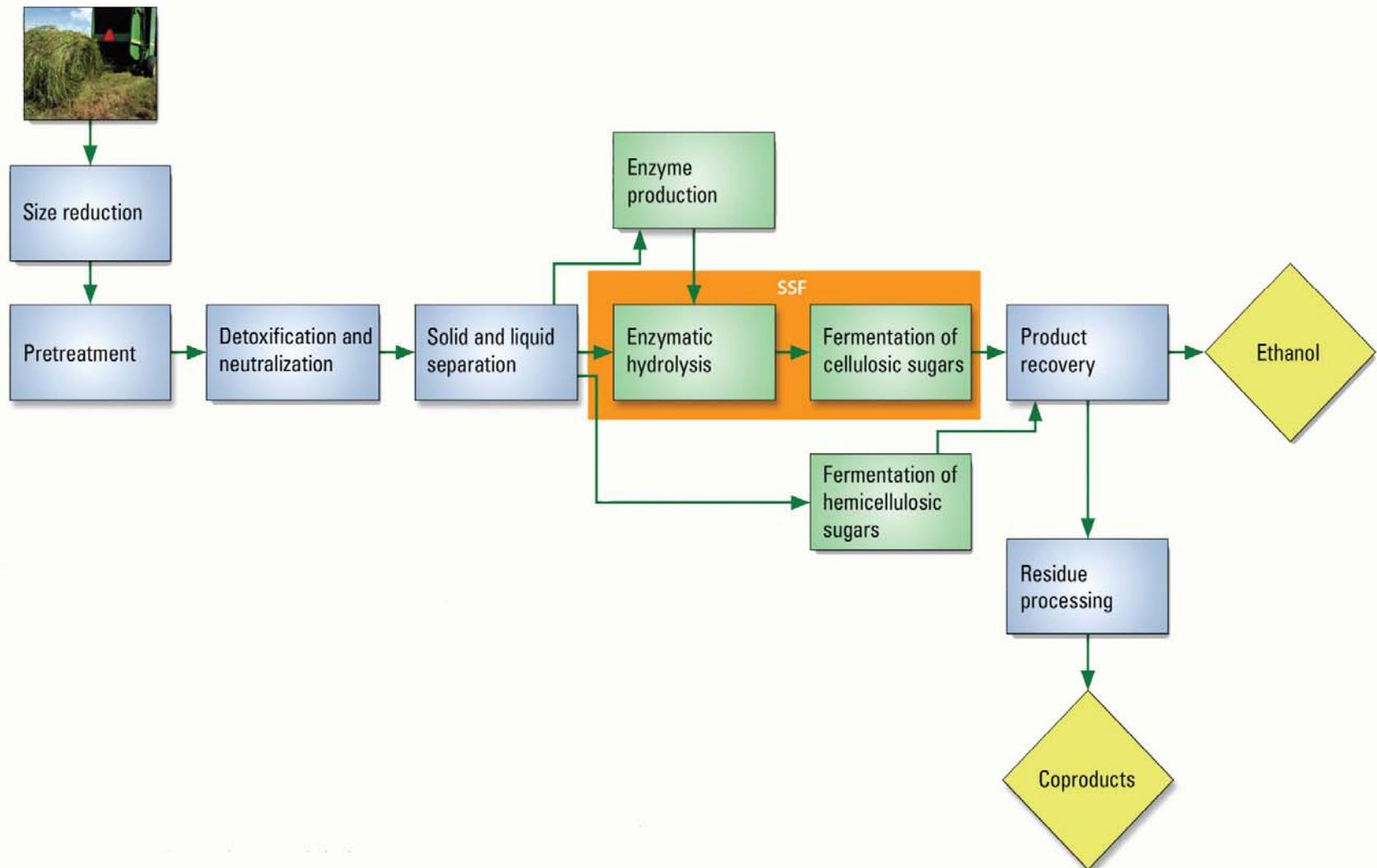


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# A DOE Ethanol Vision

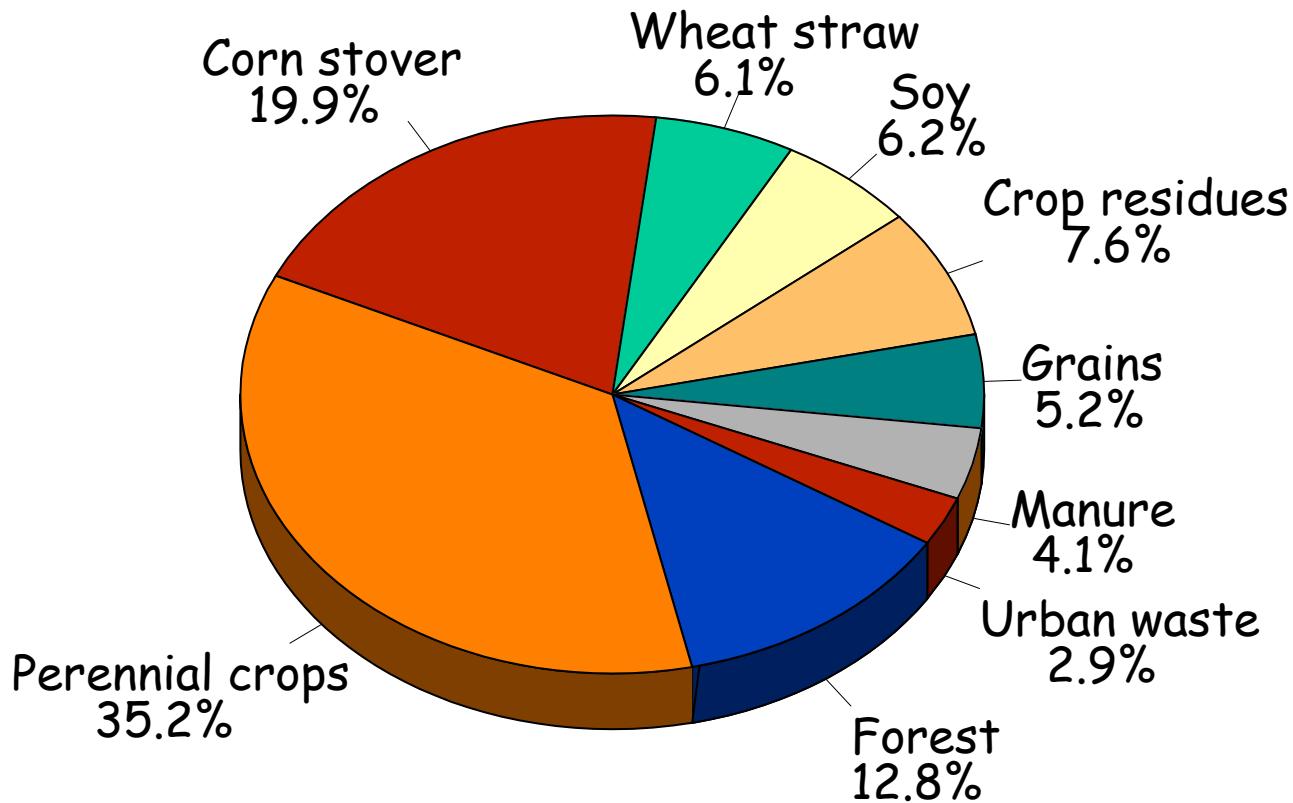


# Steps in cellulosic ethanol production



From: Breaking the Biological Barriers to Cellulosic Ethanol

US Biomass inventory = 1.3 billion tons



From: Billion ton Vision, DOE & USDA 2005

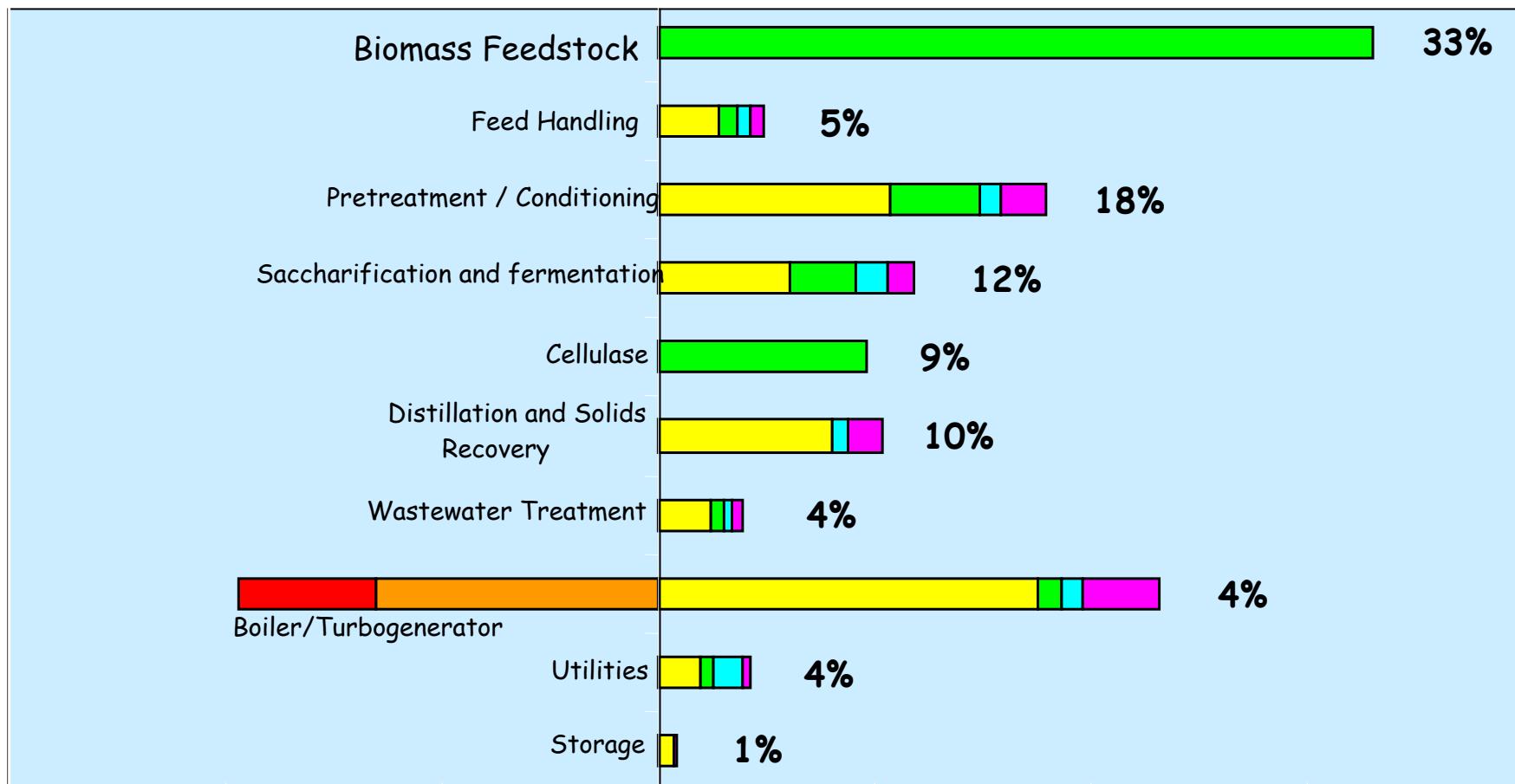
>1% yield is feasible

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

Courtesy of Steve Long et al



# Relative cost factors of cellulosic ethanol



(0.30)

(0.20)

(0.10)

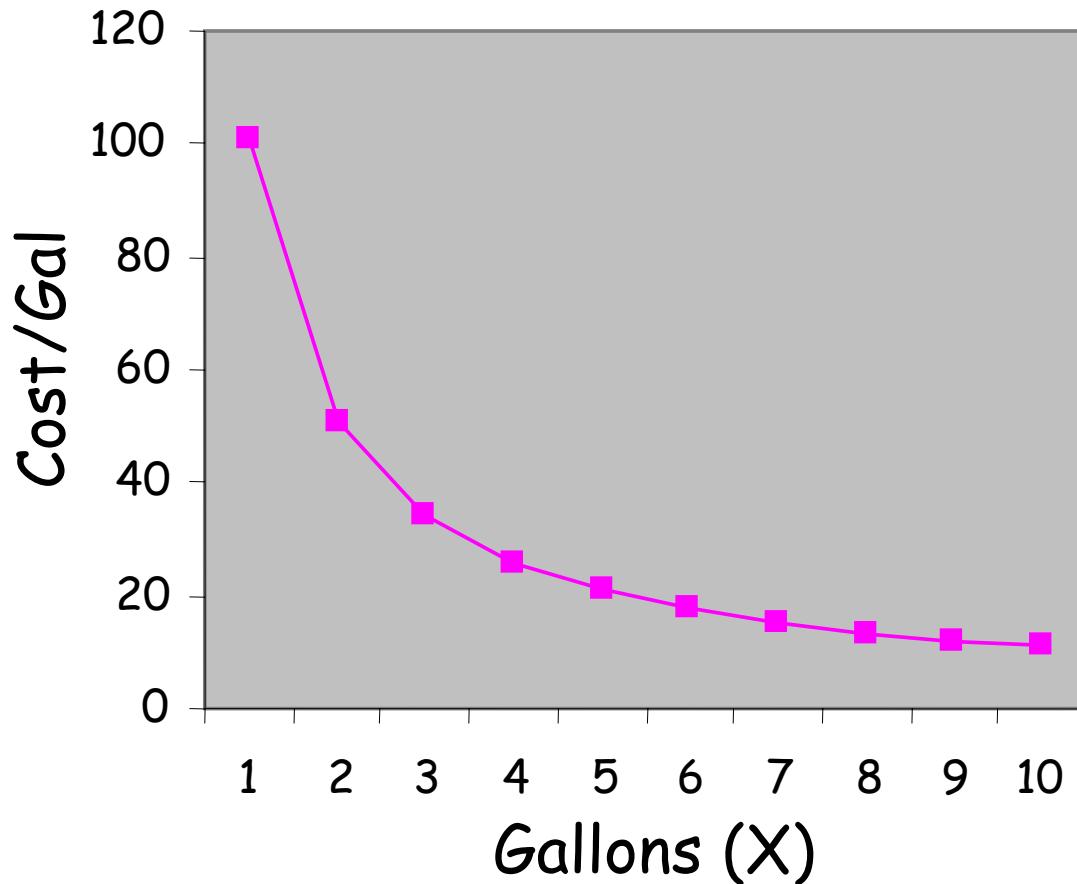
0.10

0.20

0.30

0.40

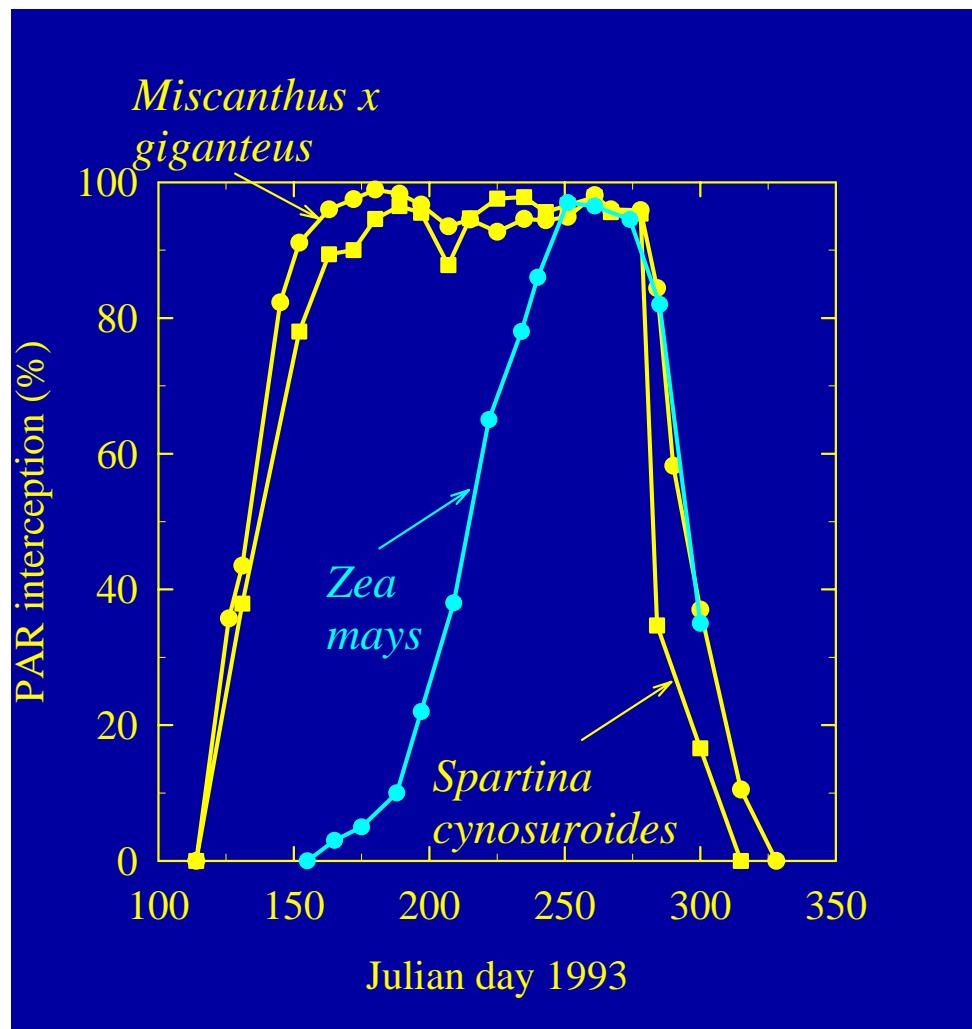
Plot of  $\text{Cost/gal} = (Y + aX)/X$



At 15 t/a, 300 Mgal  $\sim 30\%$  of all land in 20 mile radius

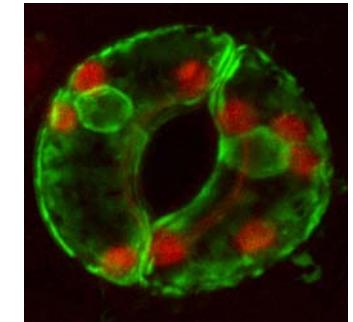
1 mi  $\times$  0.5 mi  $\times$  35 ft

# Perennials have more photosynthesis



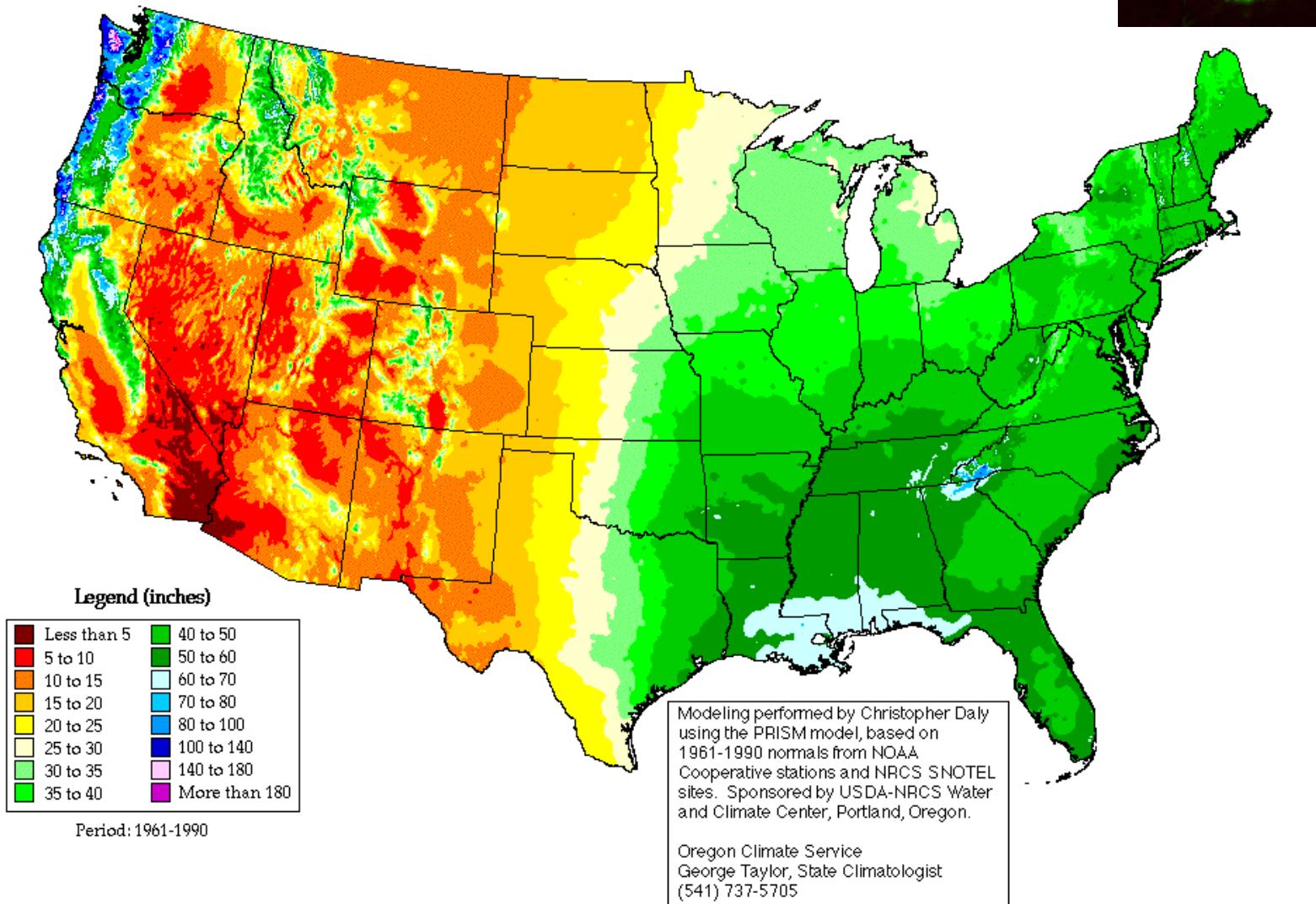
Courtesy of Steve Long, University of Illinois

# Annual precipitation

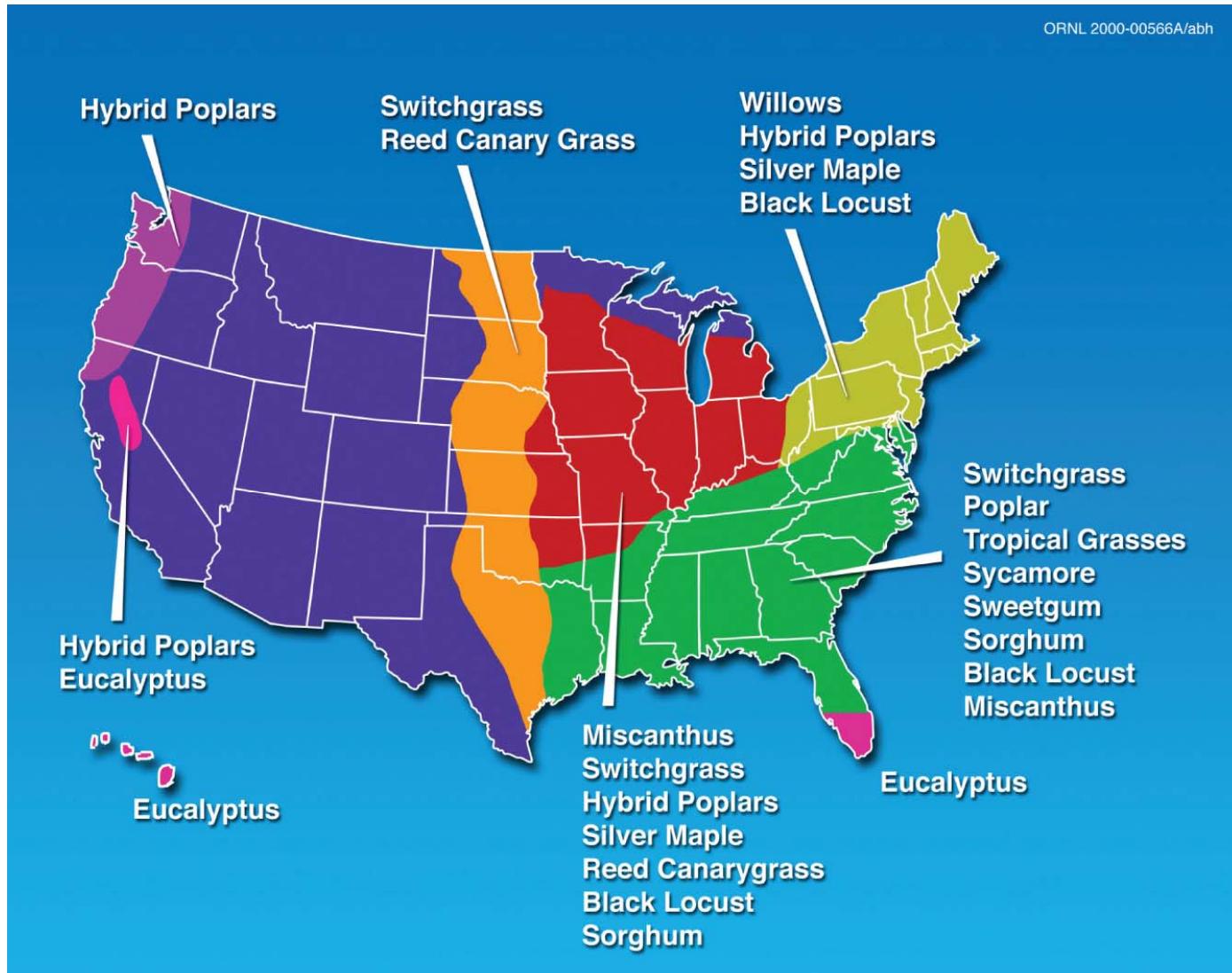


Annual Average Precipitation

United States of America



# Geographic distribution of biomass



# Economics of Perennials are Favorable

CROP	Yield per Acre	Value \$ @\$50/t	Cost \$	Profit \$
Corn	160 bu	500	193*	307
Switchgrass	10 tons	500	138**	362
Miscanthus	15 tons	750	193	557

\*USDA economic research service 2004

\*\*50% as much fertilizer, no chemicals

# Prospective energy crops have not been subject to intensive breeding



Miscanthus sp.



Switchgrass (*Panicum virgatum*)

Courtesy of Steve Long & Emily Heaton. USDA-NRCS PLANTS Database / Hitchcock, A.S. (rev. A. Chase). 1950. *Manual of the grasses of the United States*. USDA Misc. Publ. No. 200. Washington, DC.

# Advantages of perennials

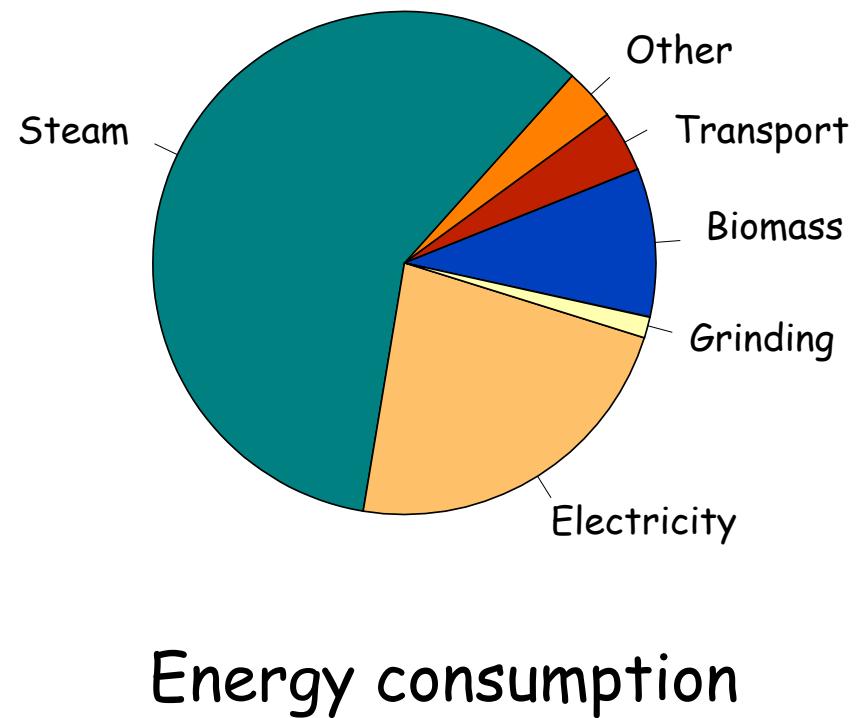
- Energy crops are expected to be more environmentally benign than production agriculture
  - Low fertilizer and chemical inputs
  - Late-harvest supports biodiversity
  - Mixed cultures possible
  - Many species can be used

# Challenges in developing energy crops

- Self-incompatibility creates challenges in breeding
- Difficult to capture adequate value from seed production
- Large capital costs in building cellulosic ethanol plants will require long-term contracts

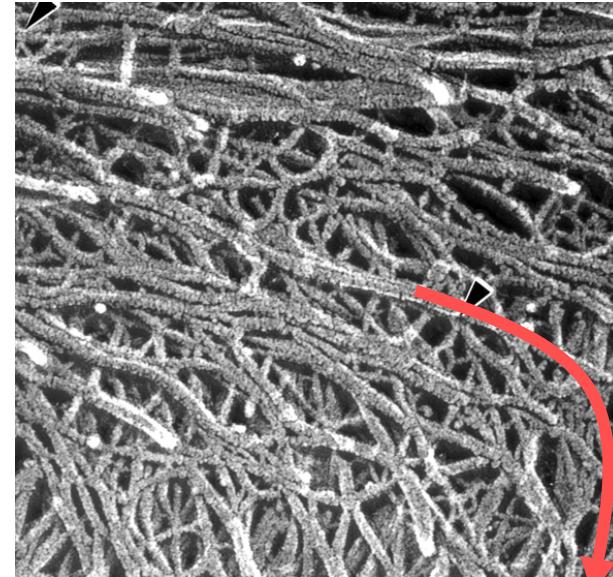
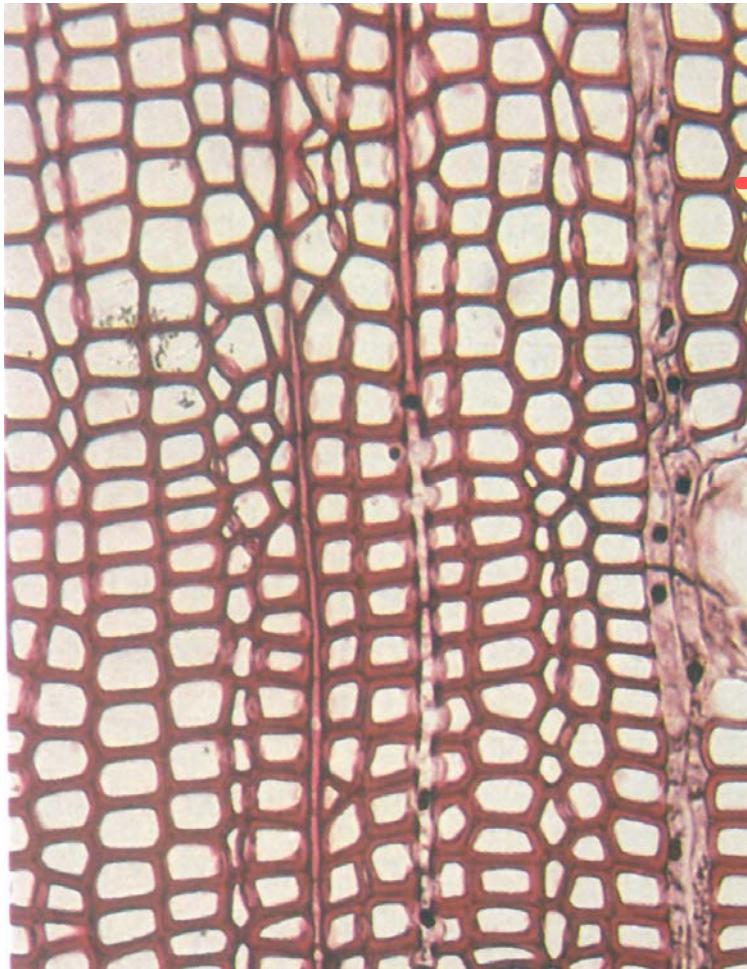
# The challenge is efficient conversion

- 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



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

# Plants are mostly composed of sugars

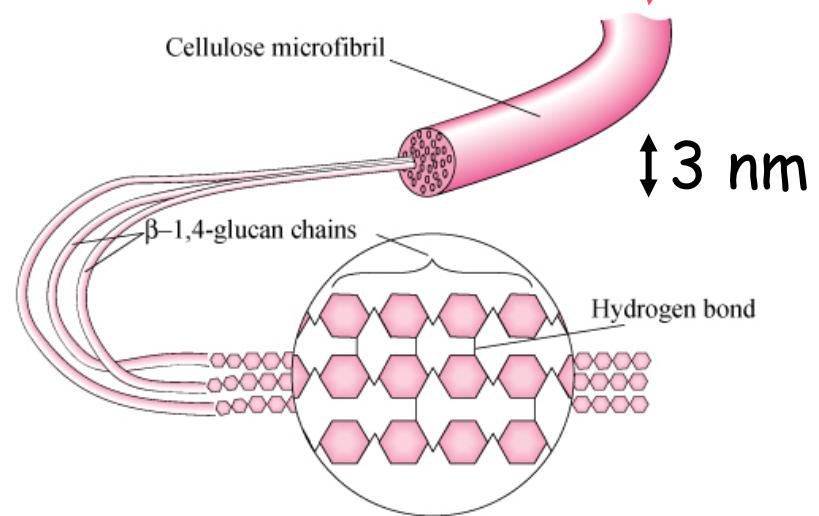


Cellulose microfibril

↔ 3 nm

$\beta$ -1,4-glucan chains

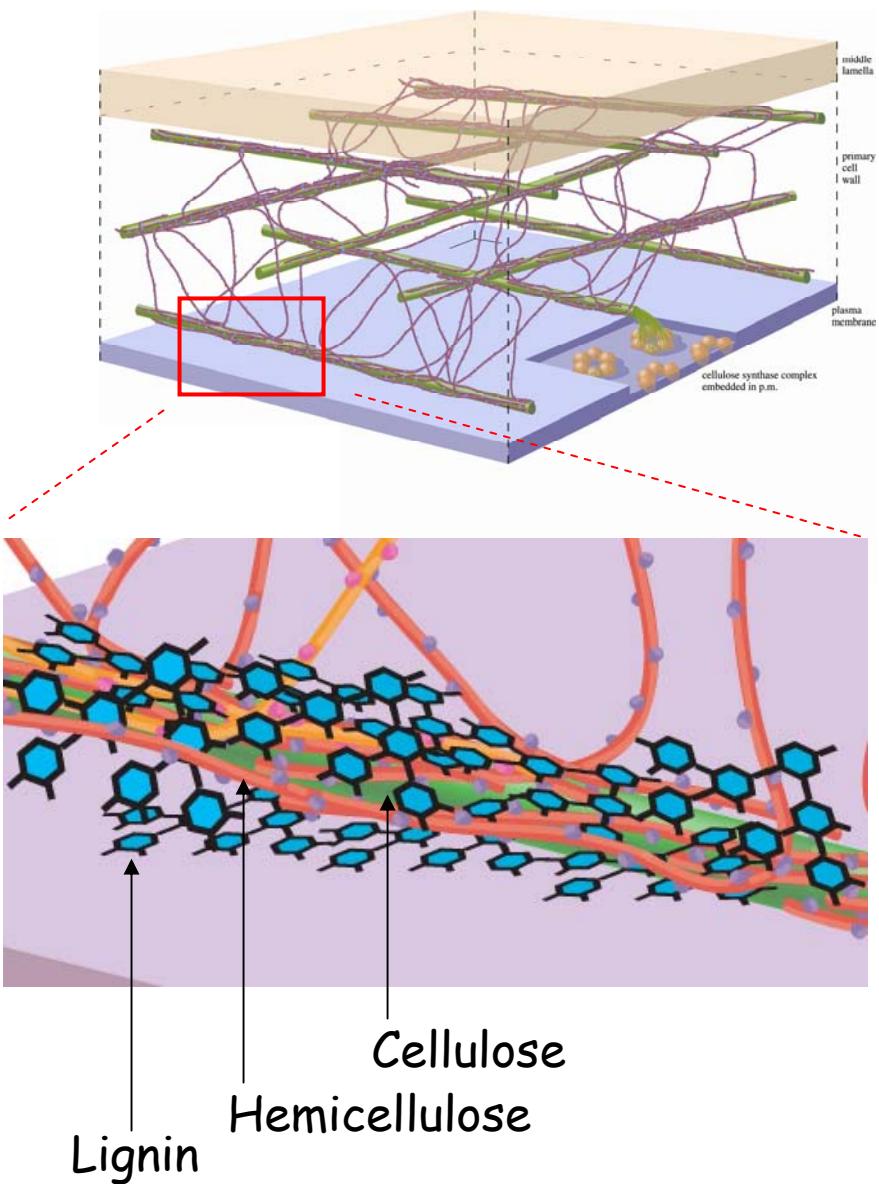
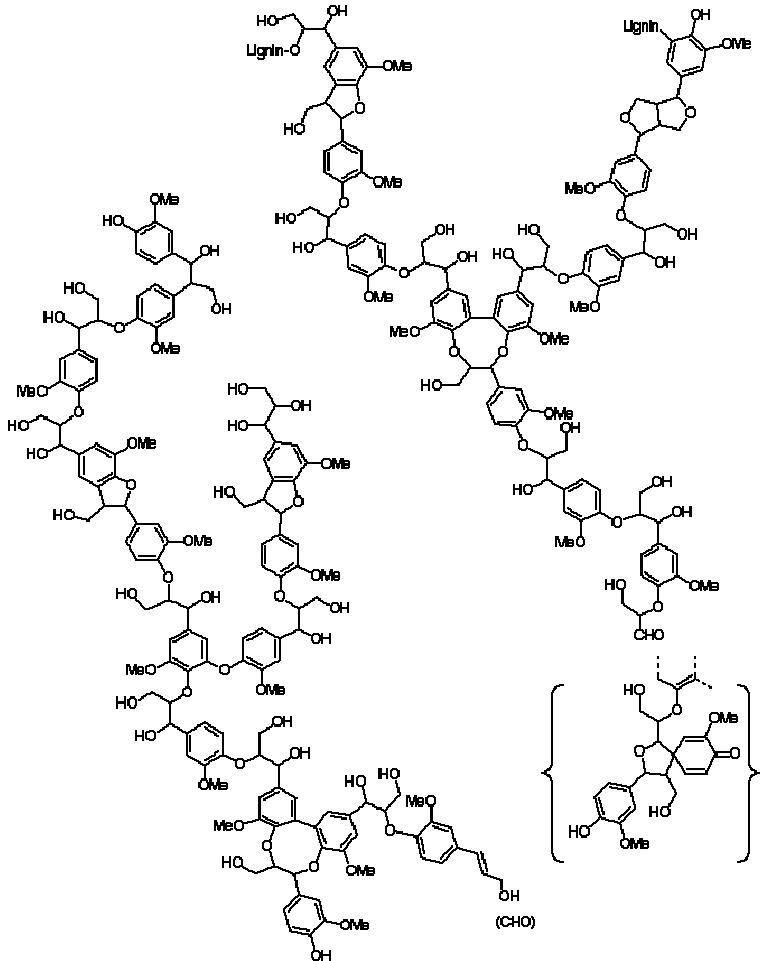
Hydrogen bond



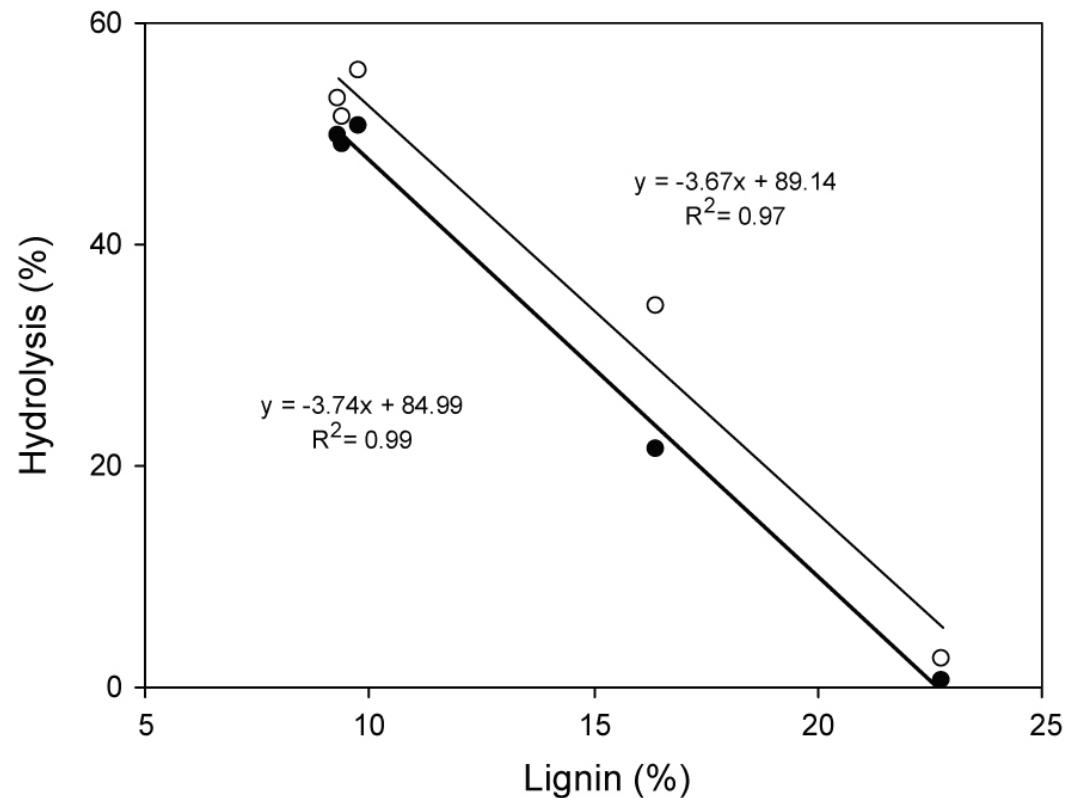
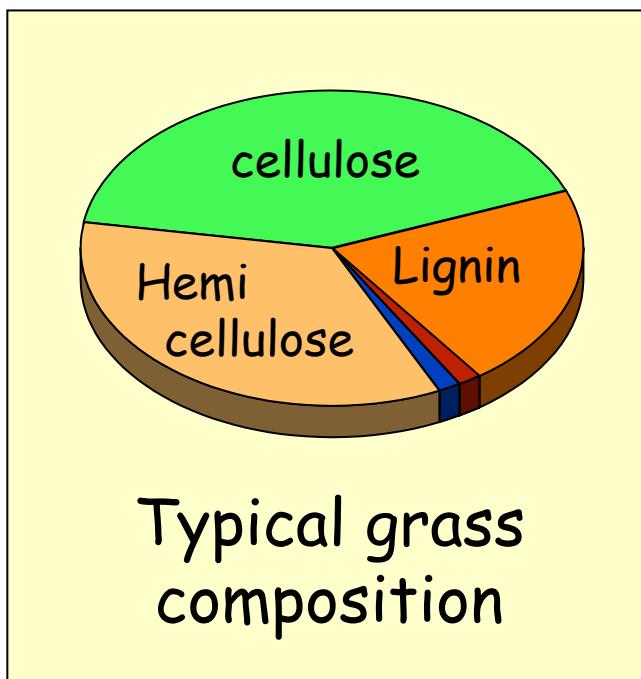
Section of a pine board

Polymerized glucose

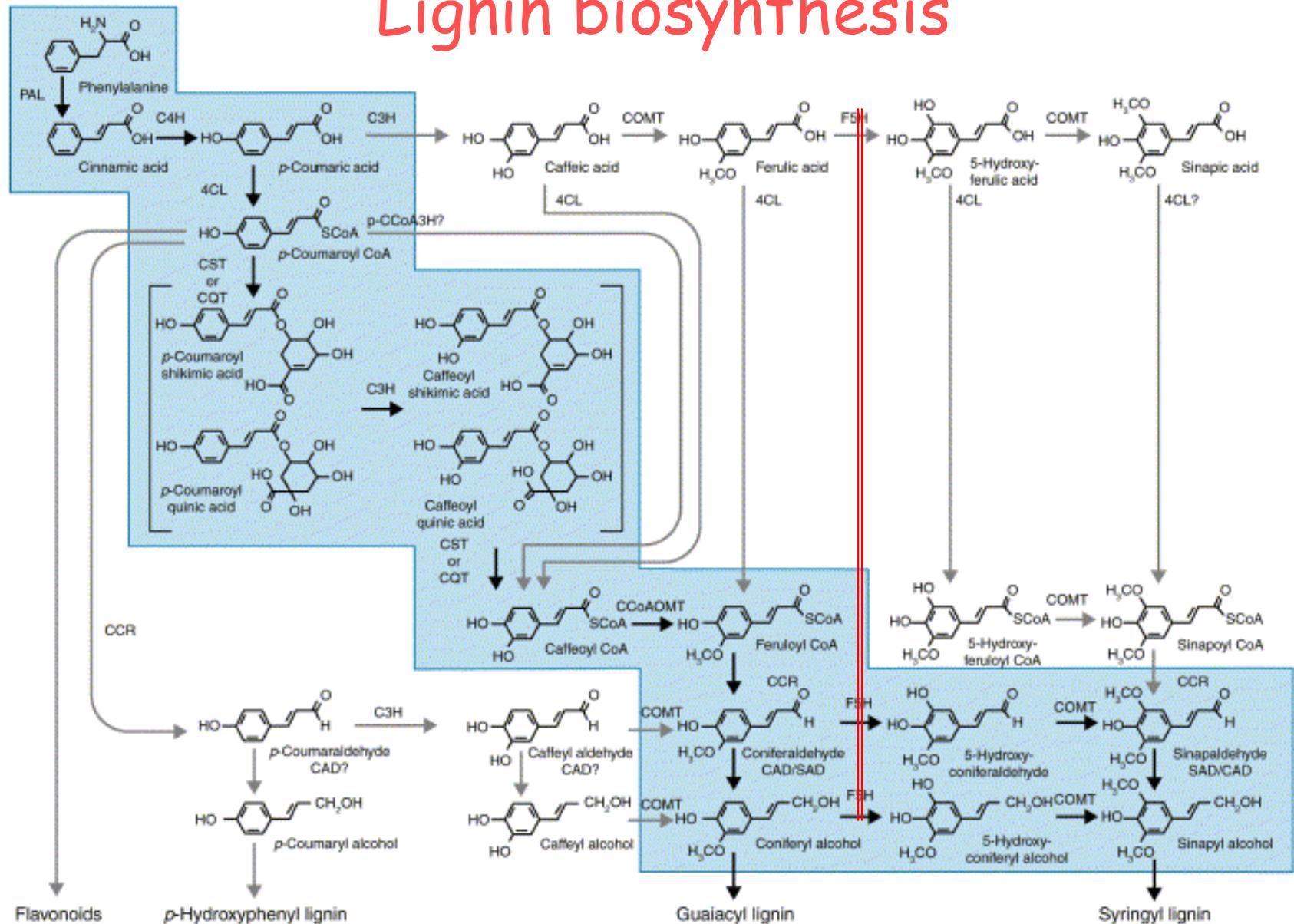
# Lignin occludes polysaccharides



# Effect of lignin content on enzymatic recovery of sugars from Miscanthus

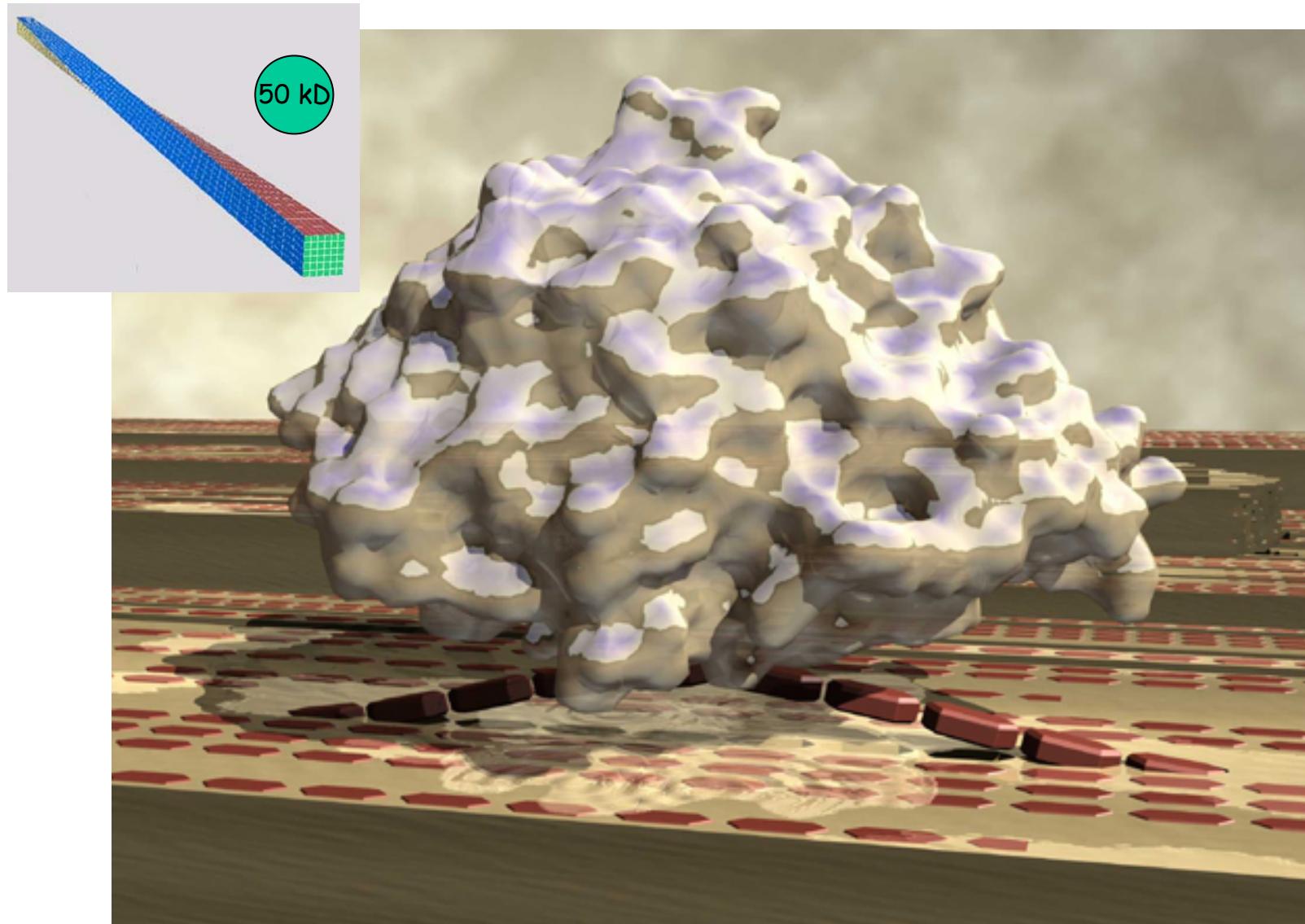


# Lignin biosynthesis



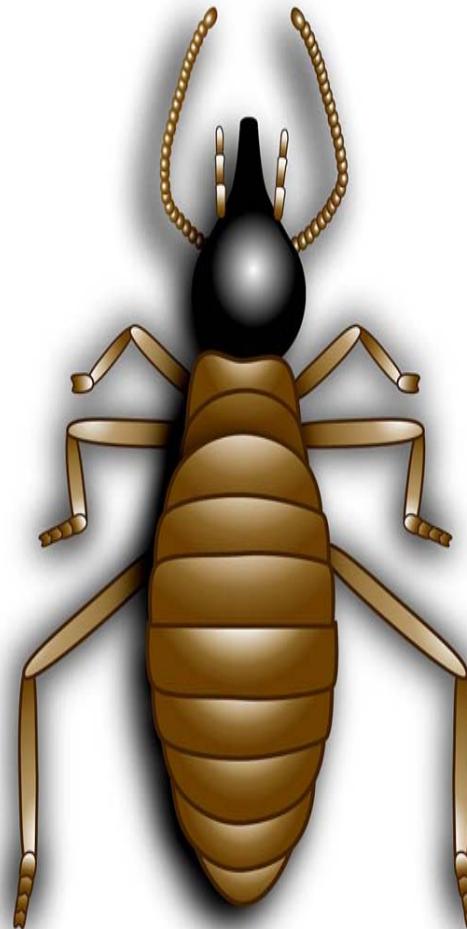
Current Opinion in Plant Biology

# Cellulose is recalcitrant to hydrolysis

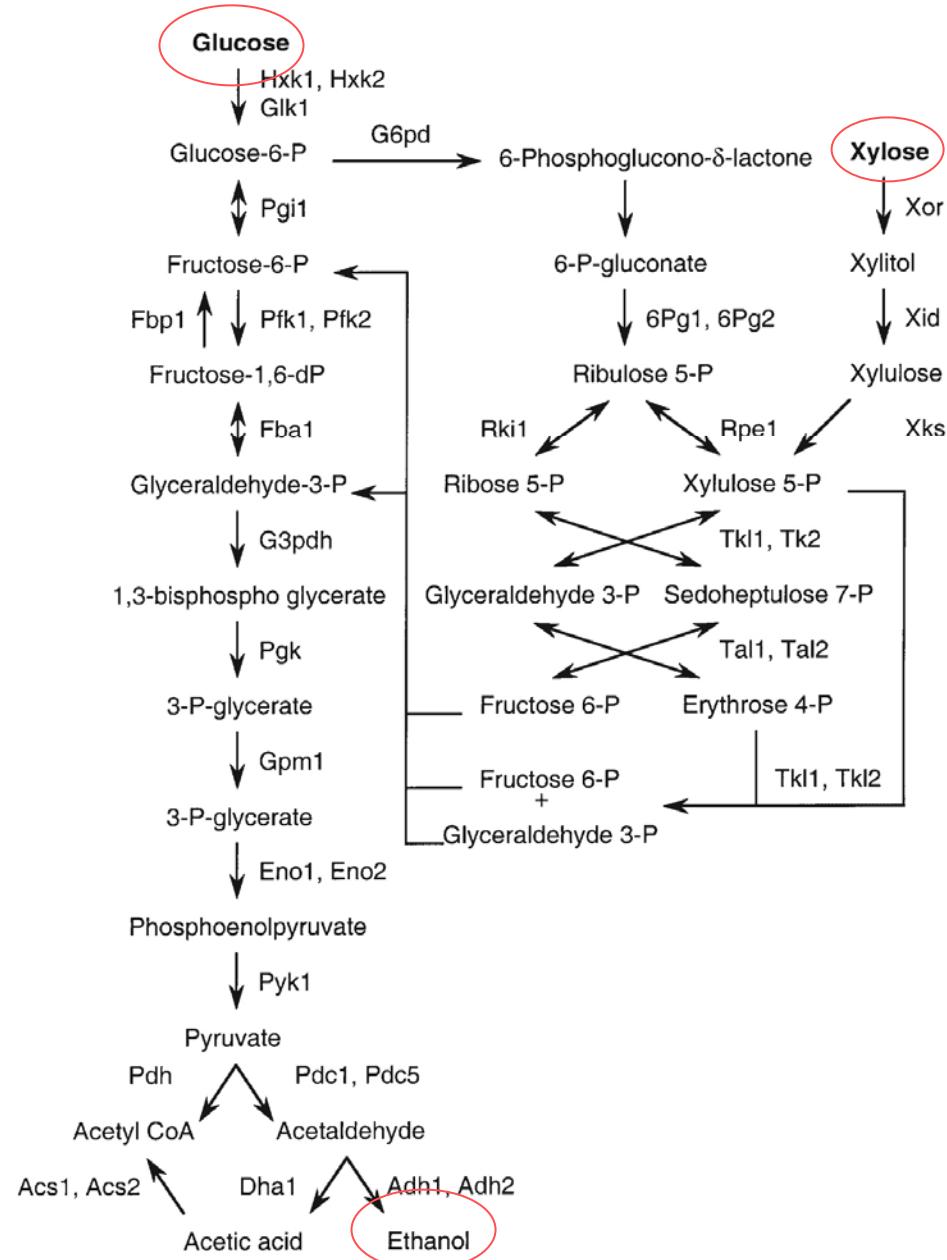
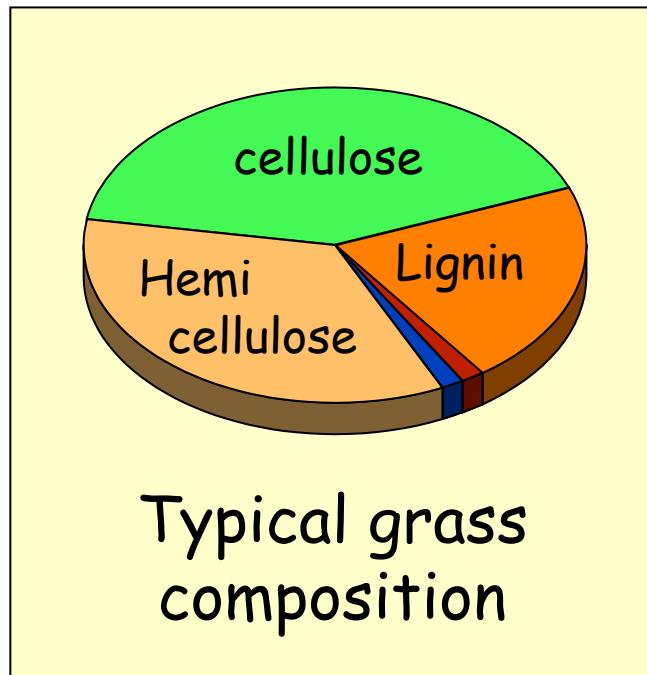


# Possible routes to improved catalysts

- 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)



# Fermentation of all sugars is essential

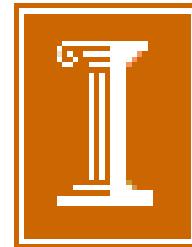


# Conclusions

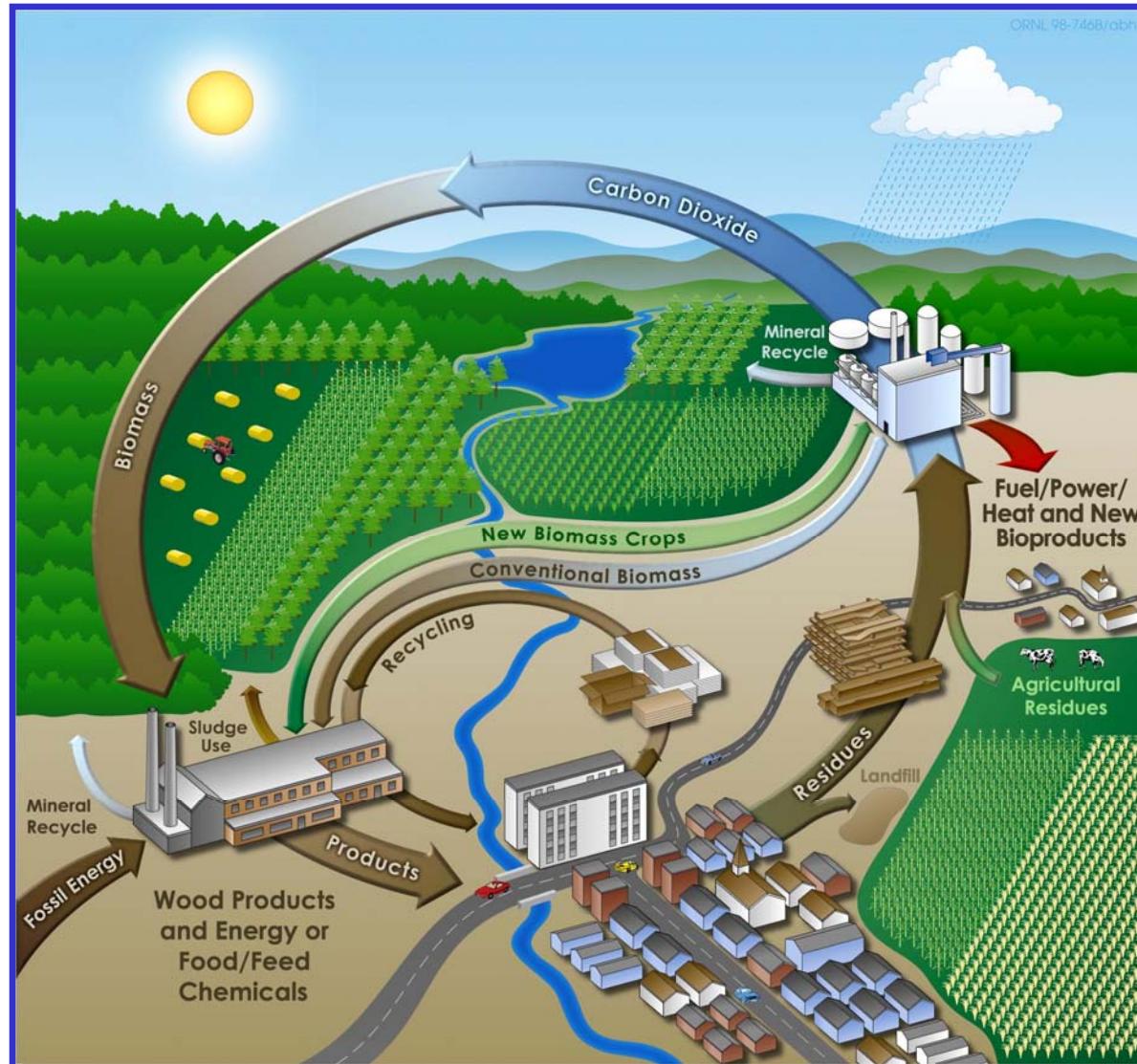
- Biofuels are expected be an important part of a carbon neutral energy economy
- There are no insurmountable problems
- Many improvements are possible
- The revolution in mechanistic biology offers enormous untapped potential to make fundamental changes in solar harvesting with plants

# The Energy Bioscience Institute

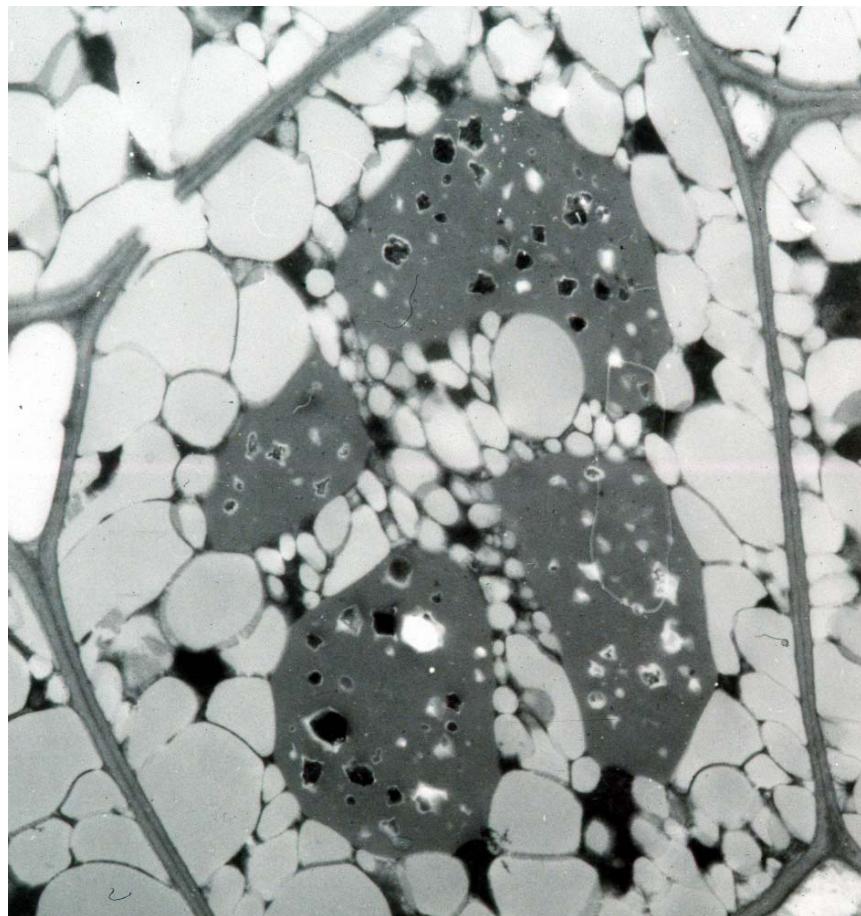
- Partnership between UCB, UI, LBL
- BP has committed \$500M over 10 years
- Goals include elimination of bottlenecks to biofuels, development of improved biotechnologies for fuel production, and education of scientists and engineers across the relevant disciplines



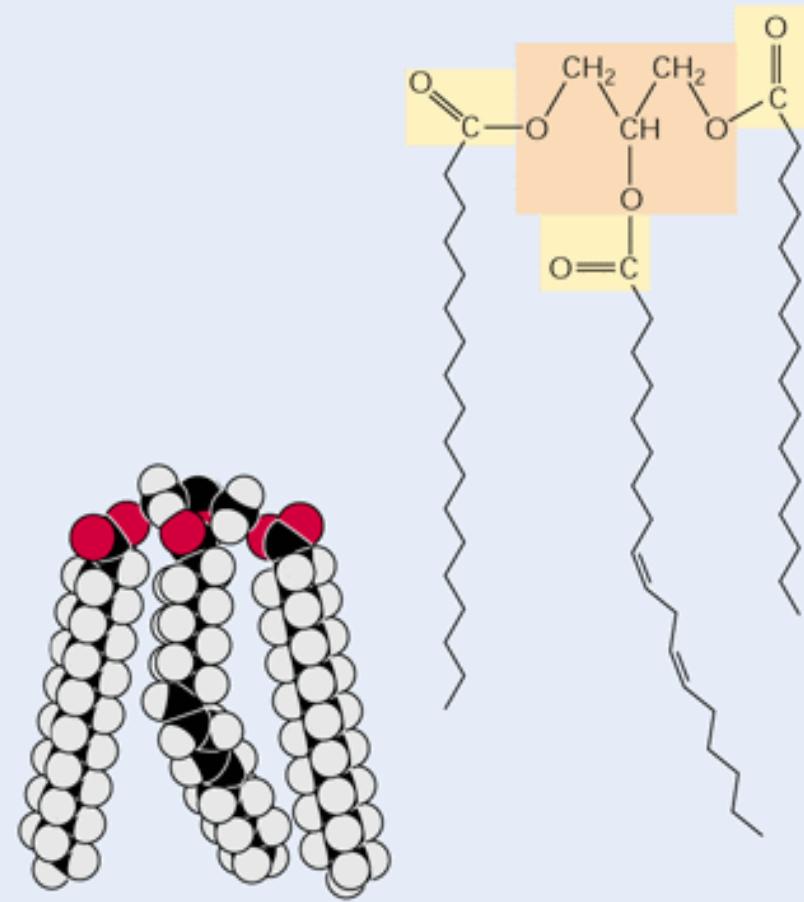
# A vision of the Future



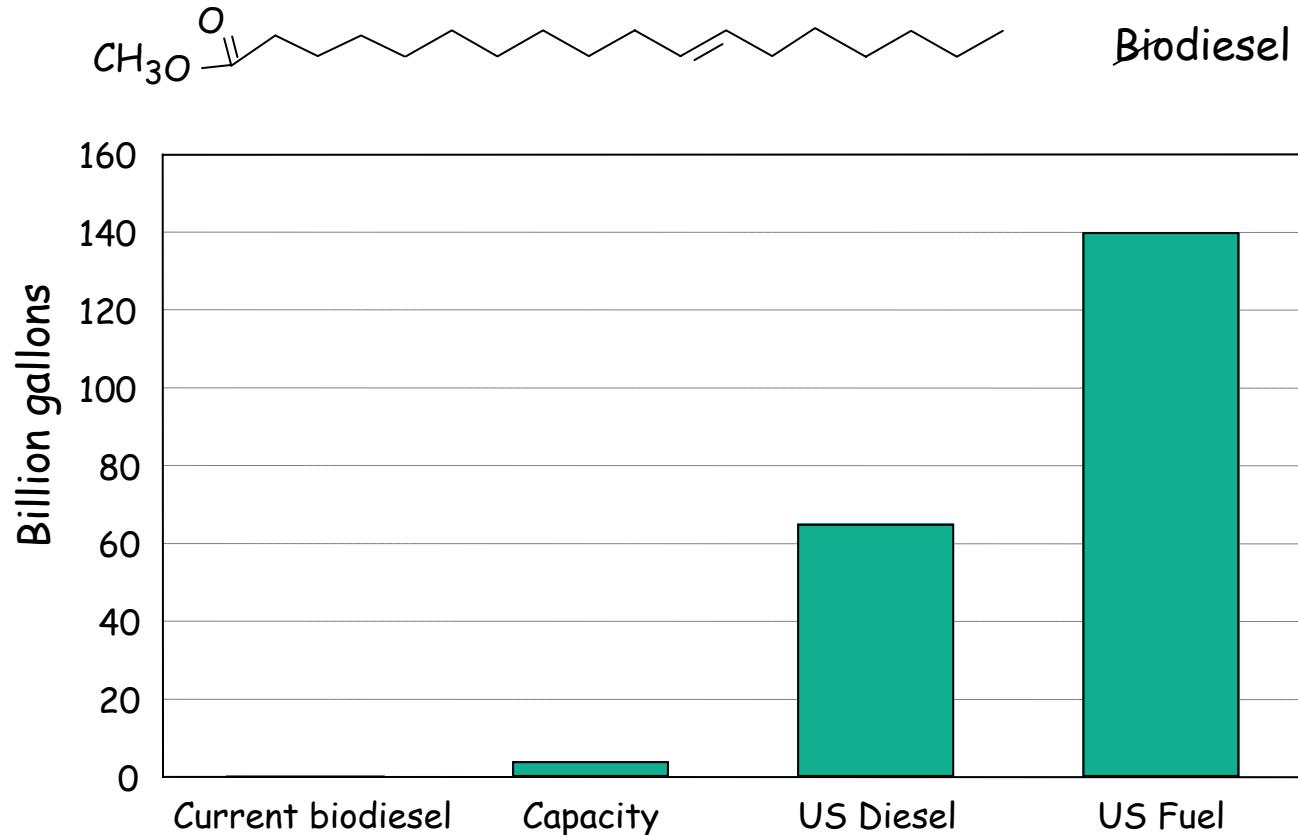
# Some plants accumulate oil



(B) Triacylglycerol



# Limited potential of biodiesel



65 biodiesel companies in operation, 50 in construction 2006