How Good Is Our Bet on Biofuels?

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RICE
Chemical and Biomolecular Engineering

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Biofuel buzz a year ago...

- Biofuels help us fight global warming by reducing greenhouse gas emissions!
- There is enough excess biomass or agricultural waste in the U.S. to produce more than 130 billion gallons of ethanol per year. This is equivalent to more than 50% of our 2005 gasoline consumption!
- Biofuels can reduce our dependence on fossil fuels and imported oil!

Sic transit gloria mundi...

"Since Congress demanded that American vehicles burn less gas and more ethanol, the price of corn has rocketed, and farm towns have boomed." But with that boom came "tortilla protests in Mexico and bread riots in Egypt."

ABC World News, 4/24/08

"Biofuels constitute a crime against humanity"

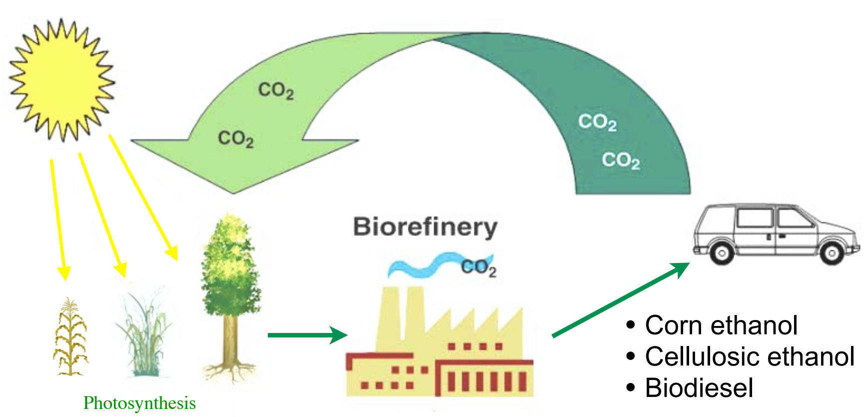
Jean Ziegler , UN Special Rapporteur for the Right to Food

"U.K. will now reconsider buying American ethanol over fears of a world crisis."

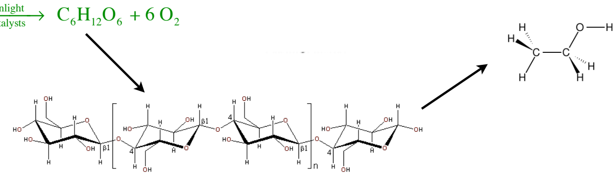
Gordon Brown, U.K. Prime Minister

"The ethanol industry blames soaring food prices on bad weather, a weak dollar, and Chinese demand. But most of all, they blame the high price of oil."

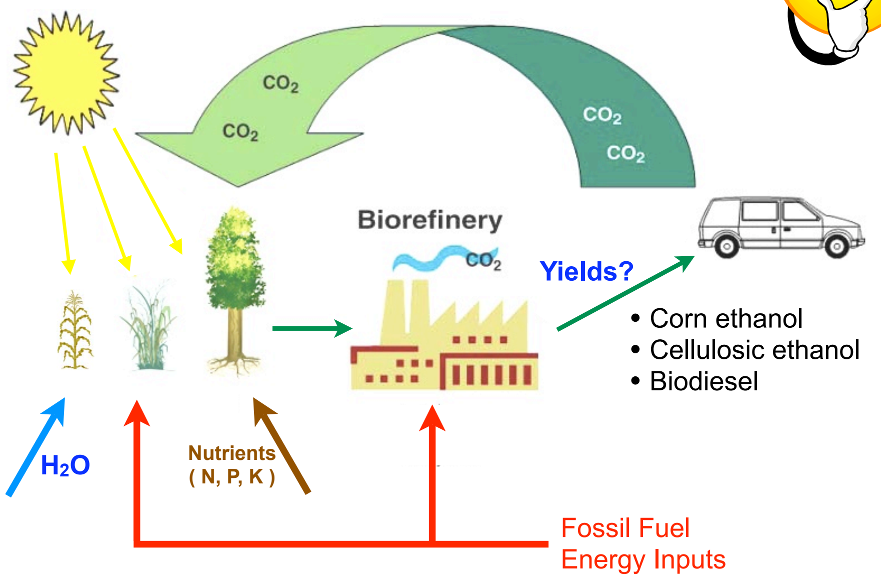
Production of Biofuels



$$6\,CO_2 + 6\,H_2O \xrightarrow[\text{catalysts}]{\text{sunlight}} C_6H_{12}O_6 + 6\,O_2$$



Complications...



Questions

- How much fuel can we produce sustainably from each source?
- How much energy do we have to spend to produce a gallon of biofuel?
- Will we reduce carbon dioxide emissions by displacing gasoline (or petro-diesel) with this biofuel?
- Are there any other effects of biofuel production on the environment? On our water resources? On food production?

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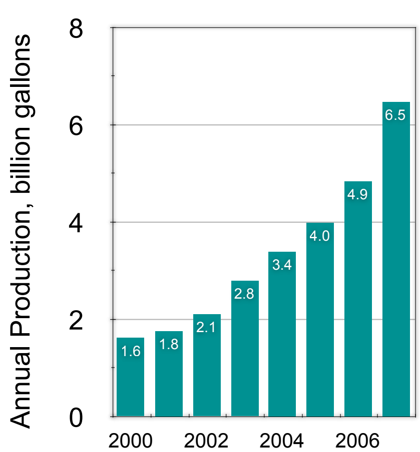
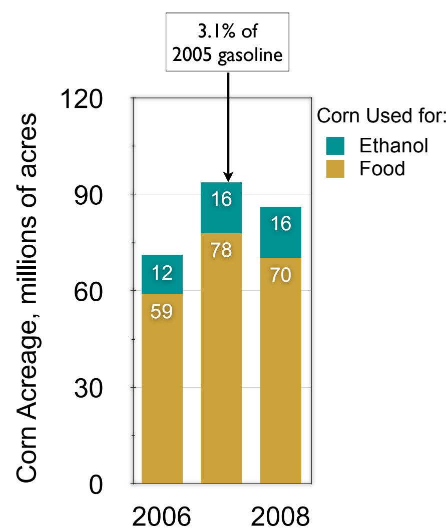
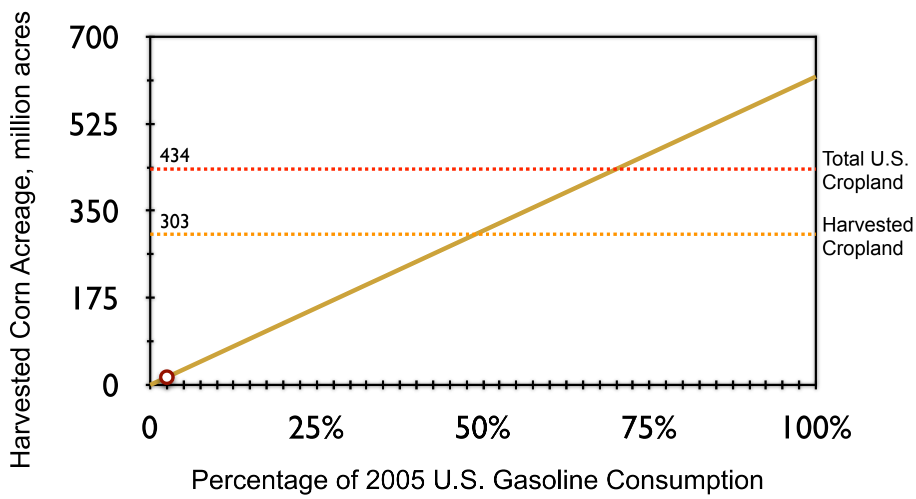
U.S. Corn Ethanol Production





Source: DOE, Energy Information Administration (EIA), 2007

Land Required to Meet U.S. Gasoline Needs with Corn Ethanol



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U.S. and Brazil

Data for 2006	U.S	Brazil
Population, million inhabitants	300	184
Total fleet of vehicles	230	28
Vehicles per inhabitant	0.77	0.15
Ethanol production, billion gallons per year	4.85	4.8
Gasoline replaced, percentage	2.5%	50%
2006: 30% of U.S. gasoline contained 10% ethanol (4.2 billion gallons)		

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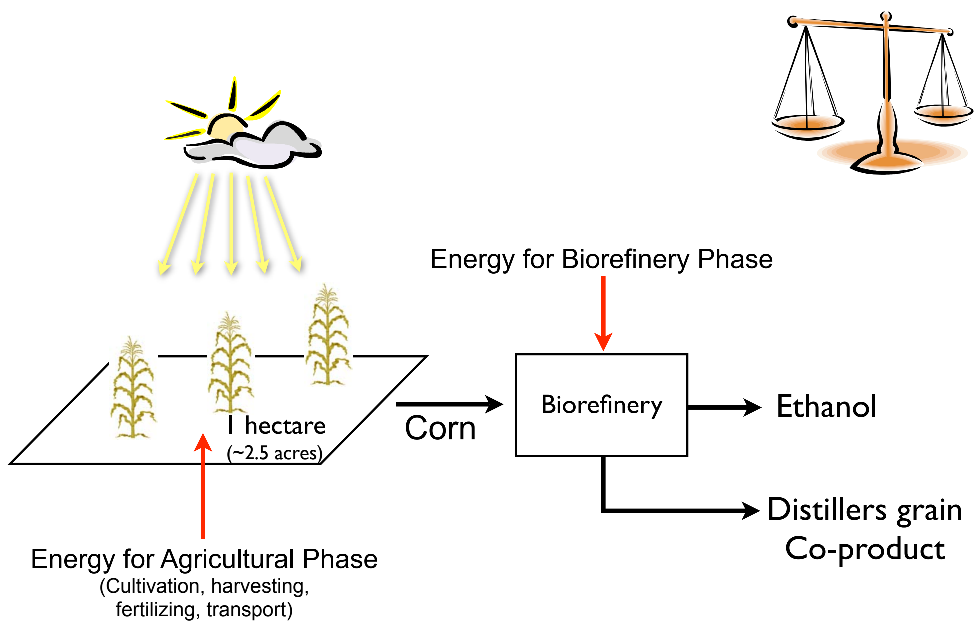
Energy Balance for Corn Ethanol



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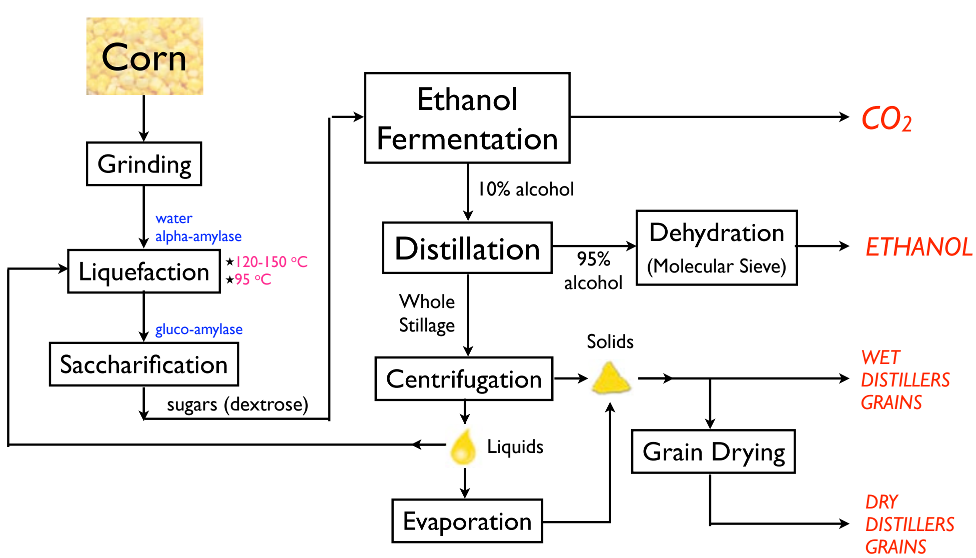
Production of Corn Ethanol



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Energy Metric

Net Energy Ratio (NER) :

$$\text{NER} = \frac{[\text{Energy Outputs}]}{[\text{Energy Inputs}]} = \frac{\begin{bmatrix}\text{Energy Content} \\ \text{of Fuel}\end{bmatrix} + \begin{bmatrix}\text{Energy Content} \\ \text{of Co-product}\end{bmatrix}}{\begin{bmatrix}\text{Energy Used in} \\ \text{Agricultural Phase}\end{bmatrix} + \begin{bmatrix}\text{Energy Used} \\ \text{in Biorefinery}\end{bmatrix}}$$

NER > 1	**GOOD**
NER< 1	**BAD**

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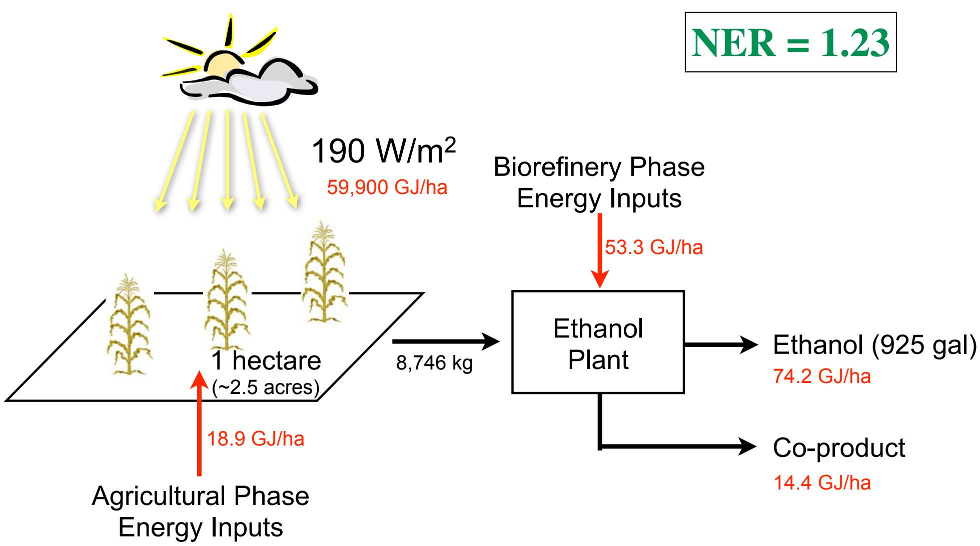
Energy Balance for Corn Ethanol

NER = 1.23



Efficiency of Solar Energy Conversion = 0.027%

Data from Farrell et al., *Science*, **181**, 506 (2006)

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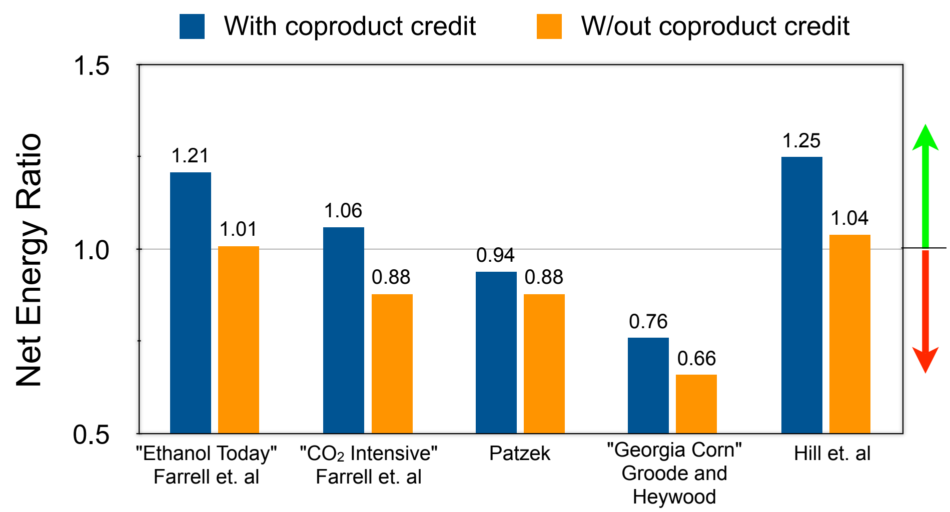
Energy Balance for Corn Ethanol



Data from Farrell et al., *Science*, ***181***, 506 (2006); Patzek, *Crit. Rev. Plant Sci*., ***23***, 519-567 (2004); Groode and Heywood, LFEE-2007-02 RP (2007); Hill et. al, *PNAS*, ***103***, 11206-11212 (2006)

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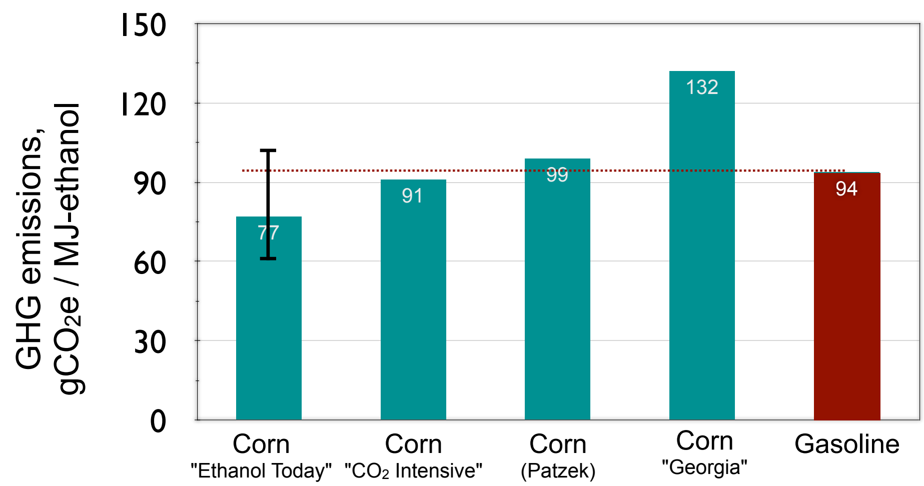
GHG Emissions for Corn Ethanol



Data from Farrell et al., *Science*, **181**, 506 (2006); * Groode and Heywood, LFEE-2007-02 RP (2007)

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Carbon Reservoirs

- Soils and plant biomass are among the largest reservoirs of terrestrial carbon.
- Together, they store between 2.5 and 4 times more carbon than the atmosphere.

Reservoir	Amount of Carbon, Gt
Terrestrial Biomass (Plants)	550 - 680
Soils	1,600 - 2,300
Atmosphere	750

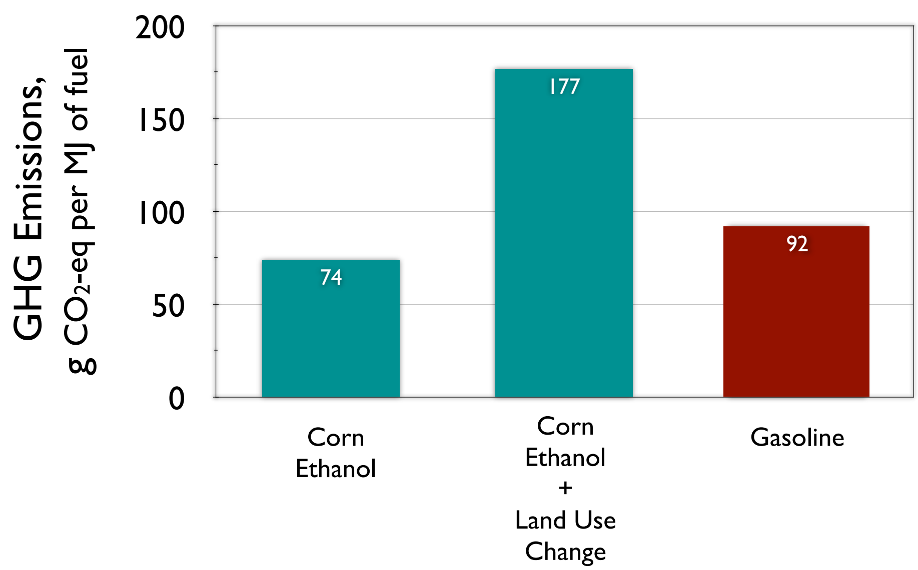
Data from: Prentice et al., "*The Carbon Cycle and Atmospheric Carbon Dioxide in Climate Change: The Scientific Basis*," Third Assessment Report of the Intergovernmental Panel on Climate Change, 2001.

Emissions from Land Use Change

- Farmers all around the world respond to the increasing demand for biofuels and the higher prices they bring by converting forest and grasslands to new croplands for biofuel production.
- As a result, land in undisturbed ecosystems is converted to biofuel production.
- Converting natural habitats to cropland releases CO_2 due to:
  - the rapid burning of biomass, and
  - the slow microbial decomposition of roots and remaining wood.
- But, previous analyses failed to account for the carbon dioxide emissions that result from such land use changes.

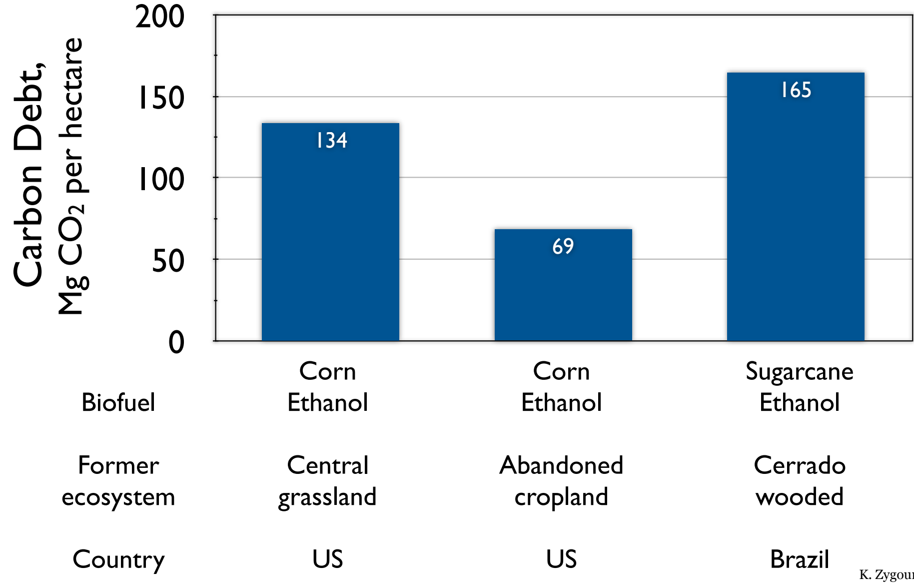
Emissions from Land Use Change

Source: Searchinger et al., *Science*, 2008.



Carbon Debt from Land Use Change

Source: Fargione et al, *Science*, 2008.



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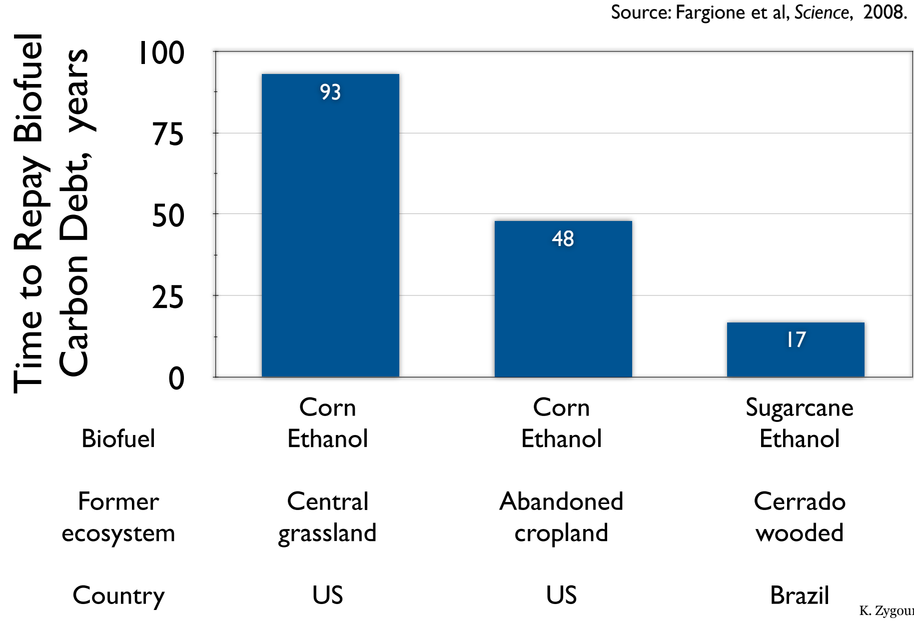

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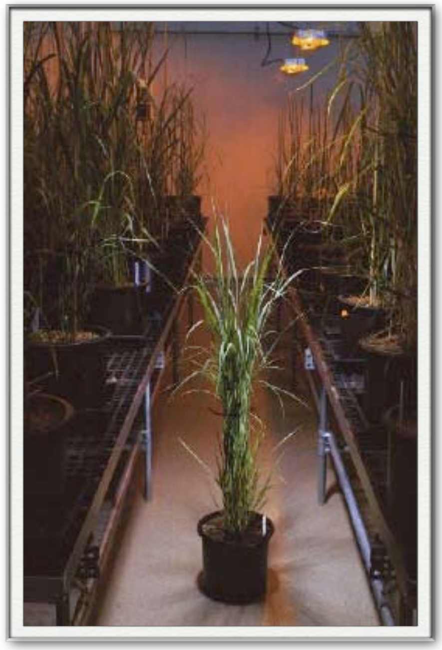
Cellulosic Ethanol

A Second Generation Biofuel



Cellulosic Ethanol

Ethanol produced from:

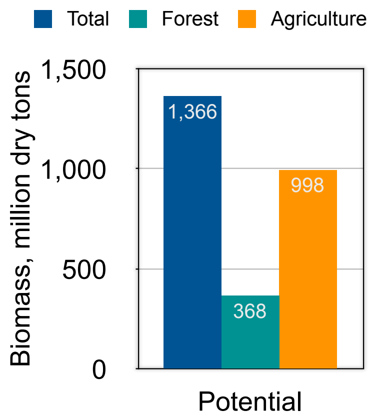
- agricultural residues (corn stover), or
- energy crops (switchgrass, poplar tree)

Corn Stover

Switchgrass

Poplar

1.3 Billion Ton Scenario



Source: U.S Department of Energy, 2005

Goal

- By 2030, replace 30% of U.S. gasoline consumption in 2004 with cellulosic ethanol.
- DOE estimate: *750 million tons of dry biomass* will be needed to produce this amount of ethanol.

Potential

- More than *1.3 billion tons of dry biomass* from forest and agricultural resources through:
  - Increased yields
  - No-till cultivation
  - Perennial crops on 55 million acres (switchgrass, poplar trees)

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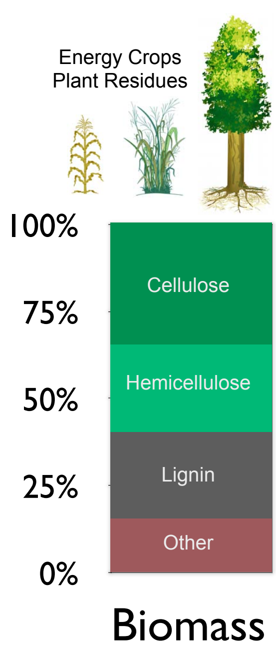
Cellulosic Ethanol Production



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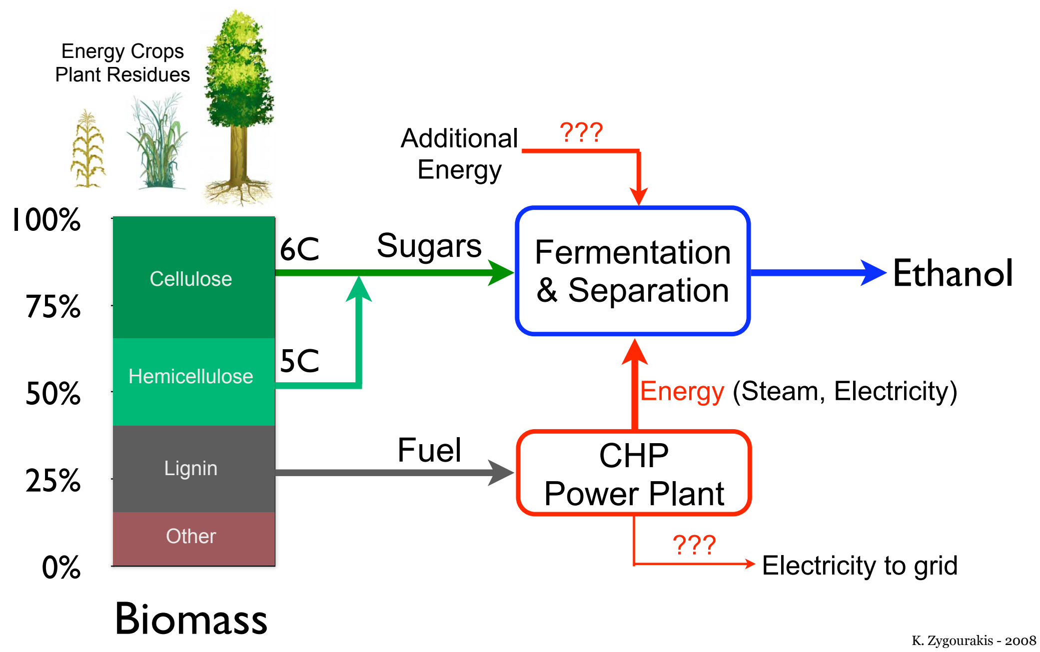
Cellulosic Ethanol Production



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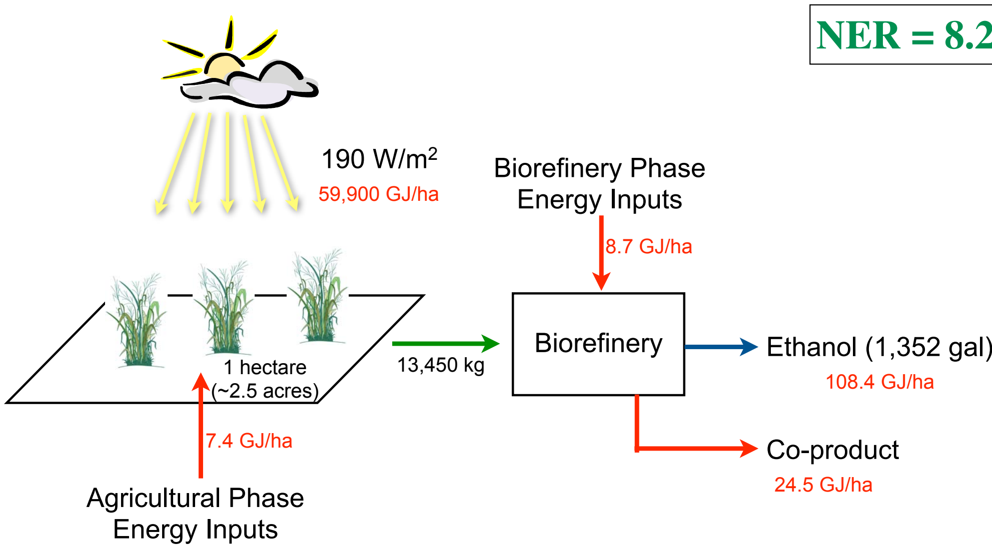
Questions:

1. What is the energy ratio for cellulosic ethanol processes?
2. How much ethanol can we produce sustainably from grasses?
3. Will there be any CO_2 savings?

EBAMM: Ethanol from Switchgrass

NER = 8.22



Efficiency of Solar Energy Conversion = 0.195%

[1] Data from Farrell et al., *Science*, **181**, 506 (2006)

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Switchgrass Annual Yields

	Crop Yield (dry tons) / ha		Crop Yield (dry tons) / ha
Industry claim - Now [a]	12.5	Lemus et al., 2002 [d] Biomass Bioenergy, 23, 433-442	6.8 - 13.1
Industry claim - Future [a]	25.0	Lewandowski et al., 2003 Biomass Bioenergy, 25, 335-361	5 - 23 Europe
Cassida et al., 2005 [b] Crop Science, 45, 673-681 and 682-692	5.82 - 14.97	McLaughlin et al., 2005 [e] Biomass Bioenergy, 28, 515-535	9.8 - 16.6 VA, TN, WV, KY, NC
Lee and Boe, 2005 [c] Crop Science, 45, 2583-2590	2 - 12	ibid	5.5-13.3 TX
Berdahl et al., 2005 Agronomy J., 97, 549-555	3.20 - 12.48	ibid	10.7-19.5 TX, AK, LA

[a] Iogen presentation; [b] Average over 3 years for upland and lowland genotypes - Annual yield depends on precipitation; [c] Annual yield depends on precipitation; [d] Average over 3 years; [e] Best 1-year yield: 34.6 Mg/ha

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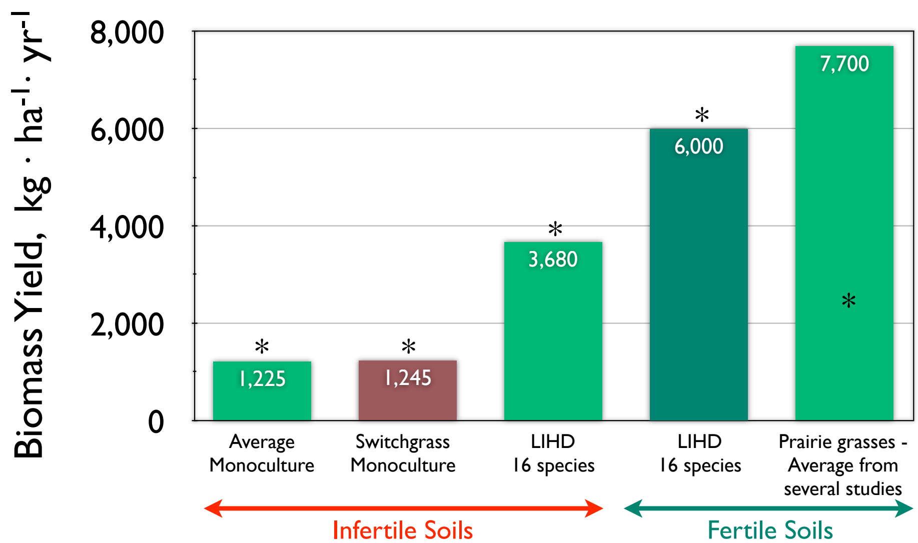
LIHD biofuels from native grasses



*Tilman et al., *Science*, **314**, 1598 (2006)

* Fargione et al., *Sciencexpress*, 10.1126/science.1152747 (2008)

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Five Scenarios for Cellulosic Ethanol

- SW-1: Data from Farrell et al. (Science, 2006) with a more realistic analysis of CHP plant.
- SW-2: Dry biomass (switchgrass) and processing step yields obtained from current literature data.
- SW-3: Same as SW-2, but with increased processing step yields to match long-term projections.
- G-4: Prairie grasses on *abandoned cropland* with long-term processing yields (Fargione et al., Science, 2008).
- G-5: Prairie grasses on *marginal cropland* with long-term processing yields (Fargione et al., Science, 2008).

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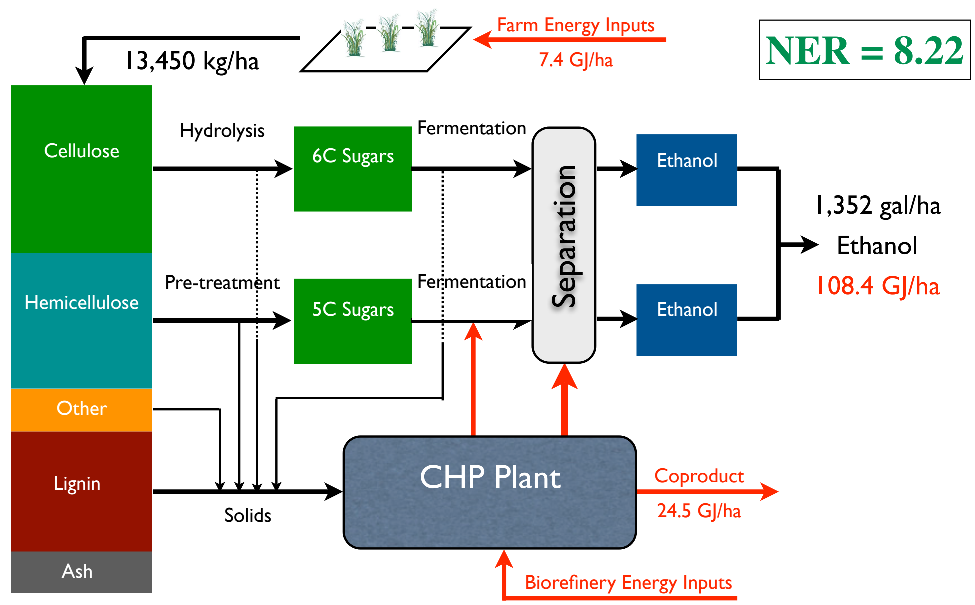
Farrell[1]: Ethanol from Switchgrass



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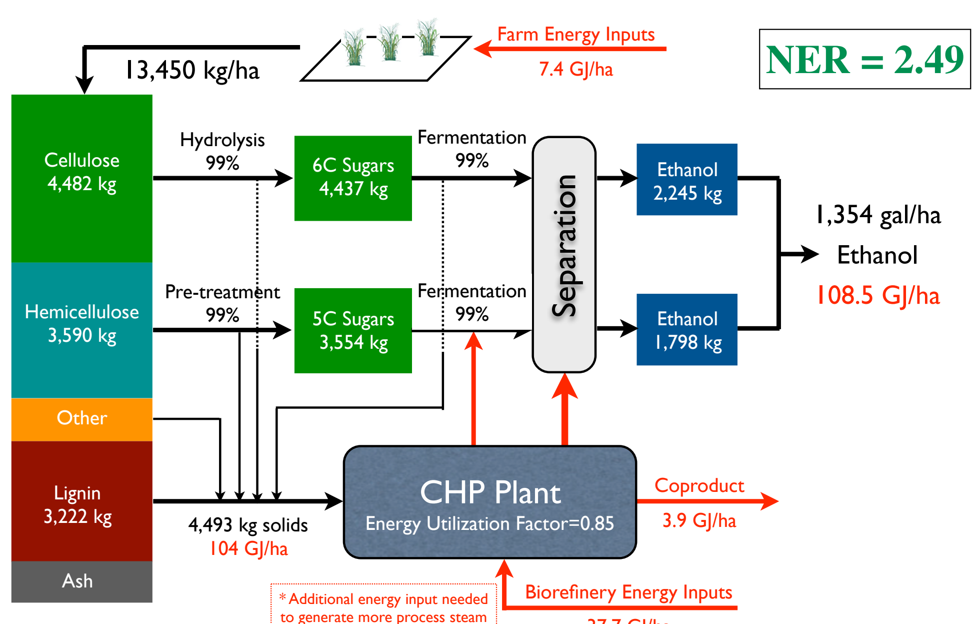
SW-1: Ethanol from Switchgrass



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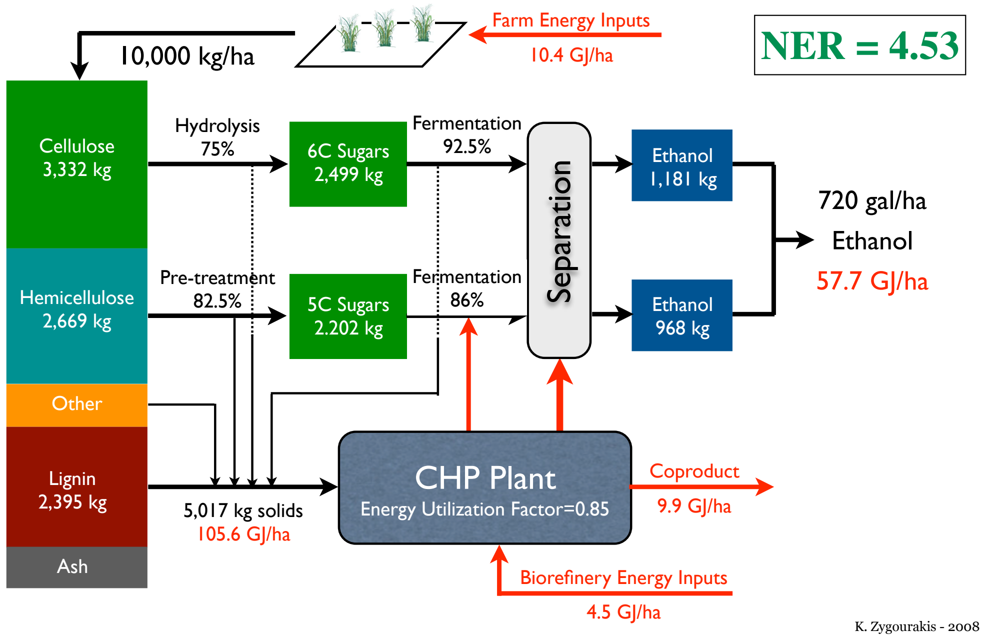
SW-2: Ethanol from Switchgrass



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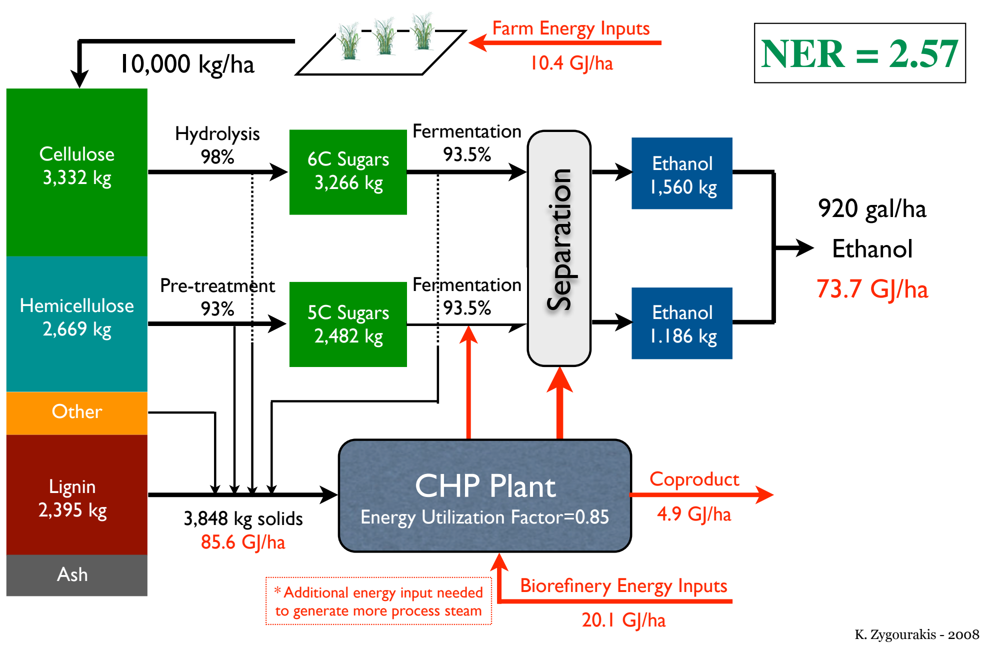
SW-3: Ethanol from Switchgrass



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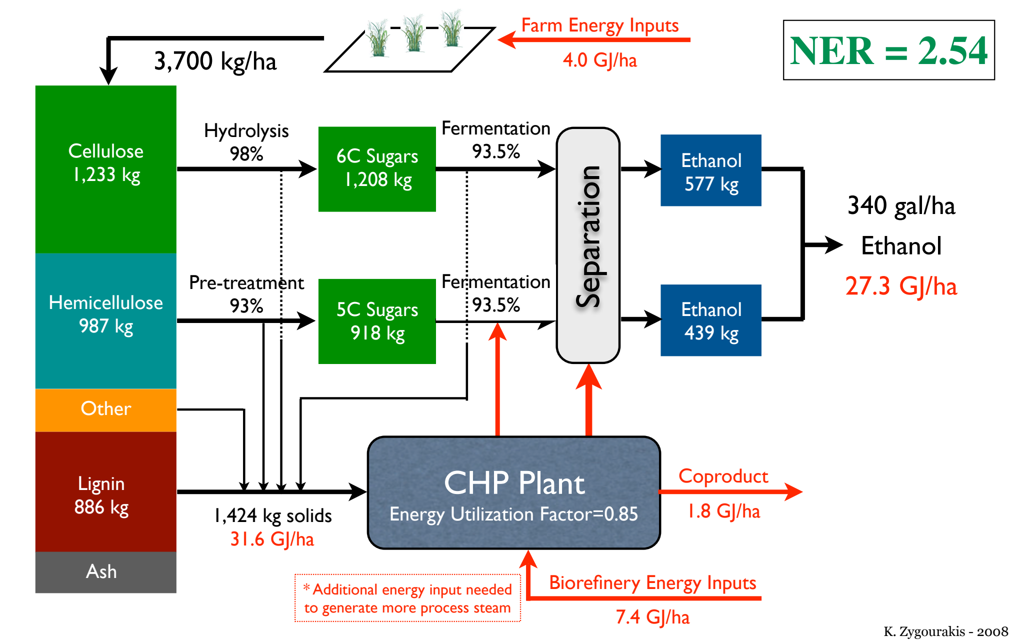
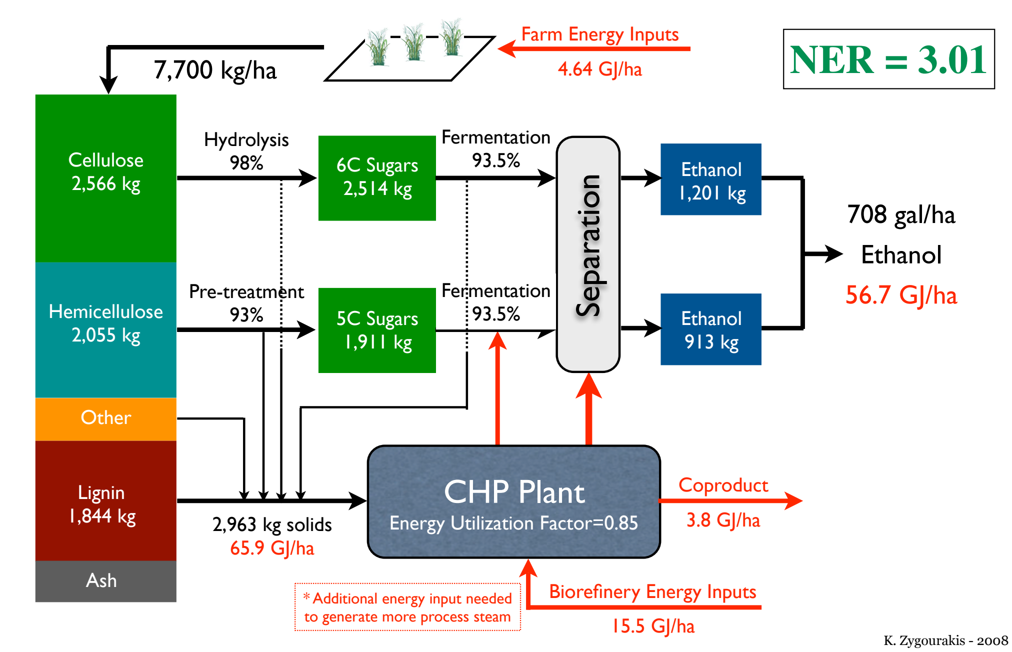
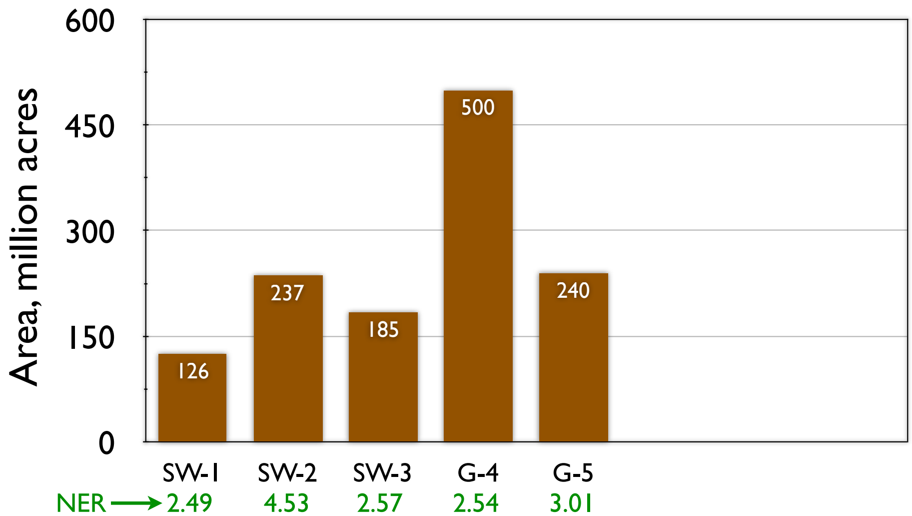
G-4: Grasses on Abandoned Cropland



G-5: Grasses on Marginal Cropland



Land Required to Meet 30% of 2005 U.S. Gasoline Needs



SW-1: Switchgrass - Farrell et al., Science, 181, 506 (2006)
SW-2, SW-3: Switchgrass with current and future technology
G-4: Prairie grasses on abandoned cropland
G-5: Prairie grasses on marginal cropland

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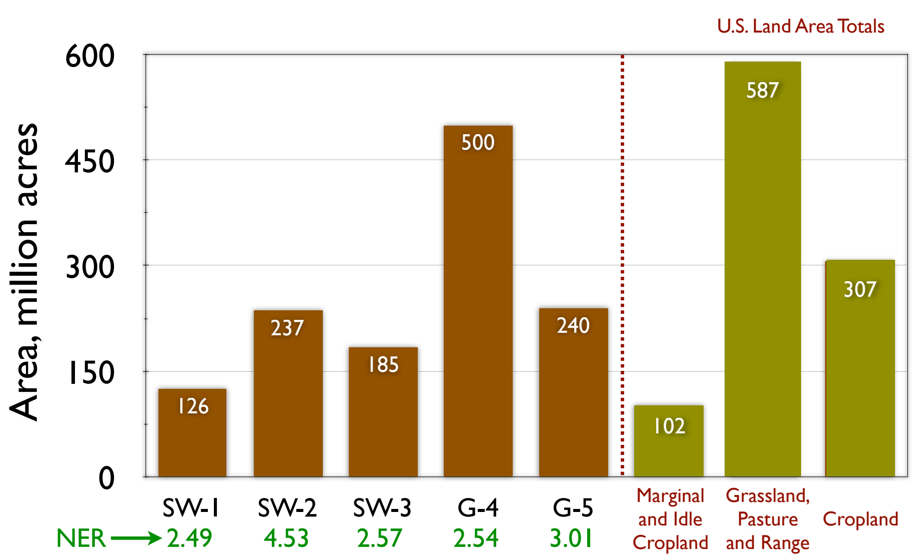
Land Required to Meet 30% of 2005 U.S. Gasoline Needs



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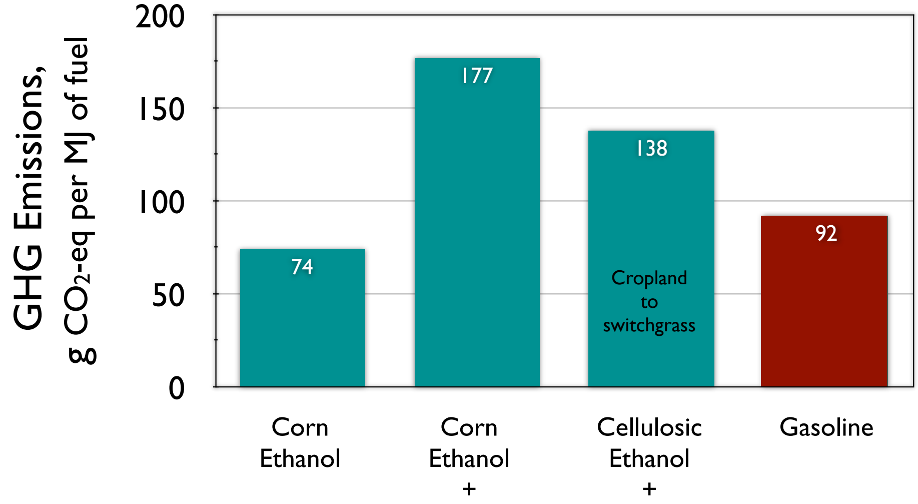
Emissions from Land Use Change

Source: Searchinger et al., *Science*, 2008.



* Land use change emissions amortized over 30 years

Prairie grasses have extensive root systems

Roots are 2/3 of the total plant biomass!

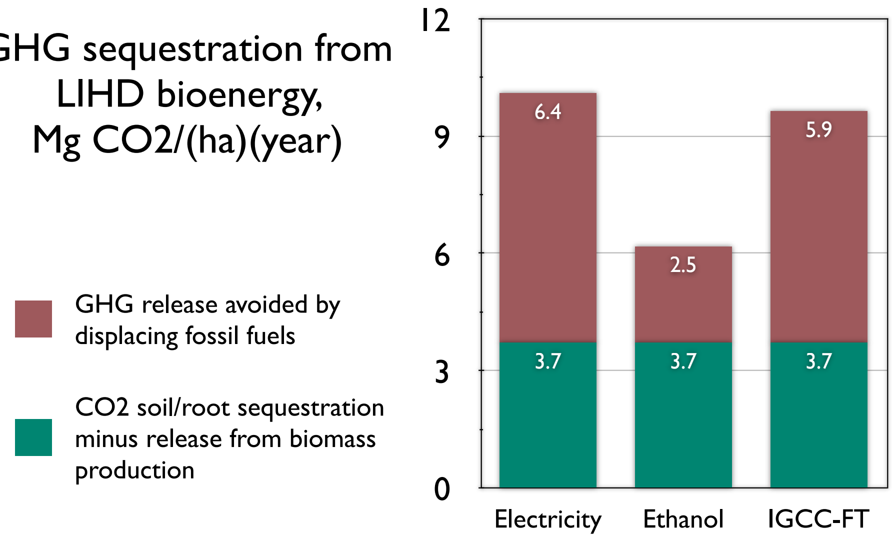
For the first 10 years

CO_2 sequestered in roots and soil: 4.4 Mg ha^{-1} yr^{-1}

Source: Tilman et al., *Science*, **314**, 1598 (2006)

LIHD biofuels are carbon negative

GHG sequestration from LIHD bioenergy, Mg CO2/(ha)(year)



Source: Tilman et al., *Science*, **314**, 1598 (2006)

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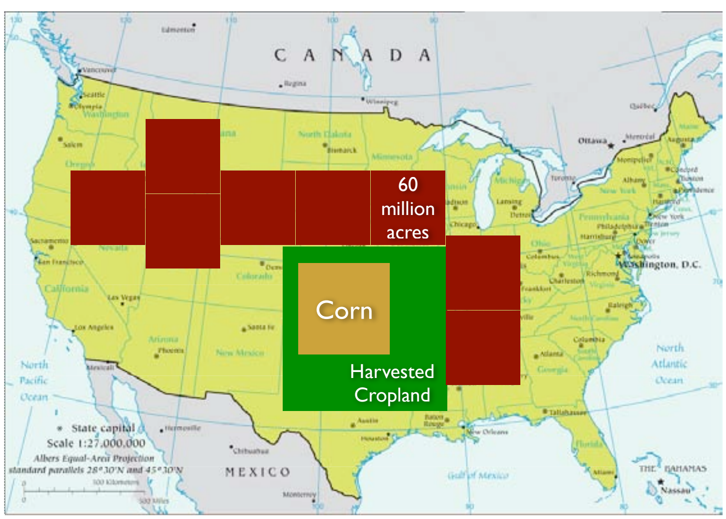
How much land will we need?



US Statistics

Total Farmland = 938 million acres
Total Cropland = 434 million acres
Harvested Cropland = 303 million acres

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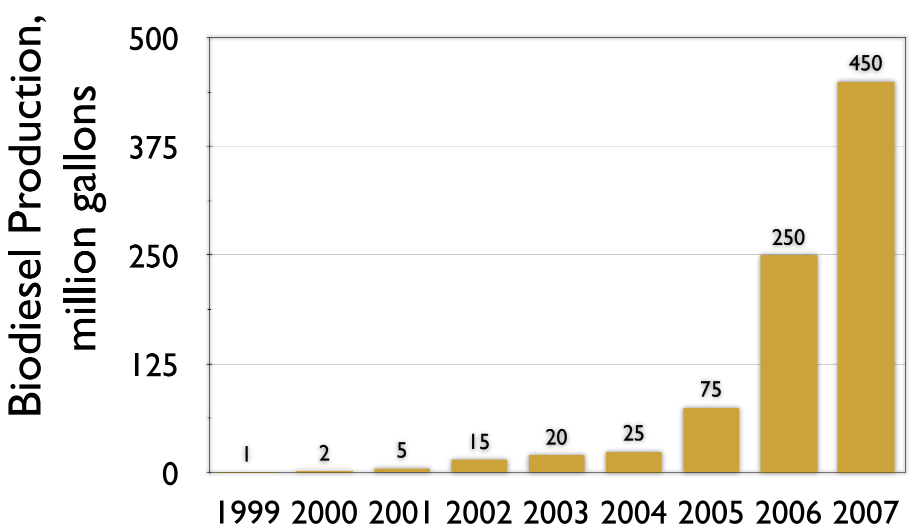
Biodiesel

US Biodiesel Production



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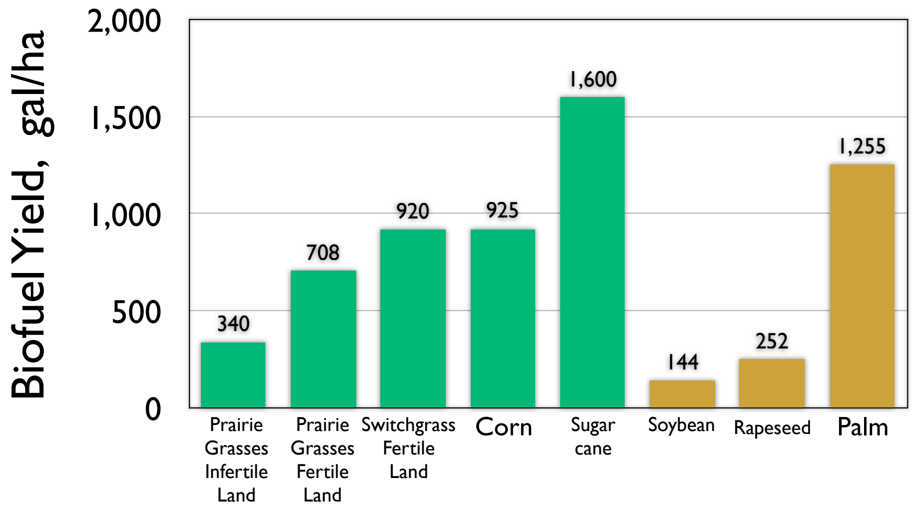
Biofuel Yields



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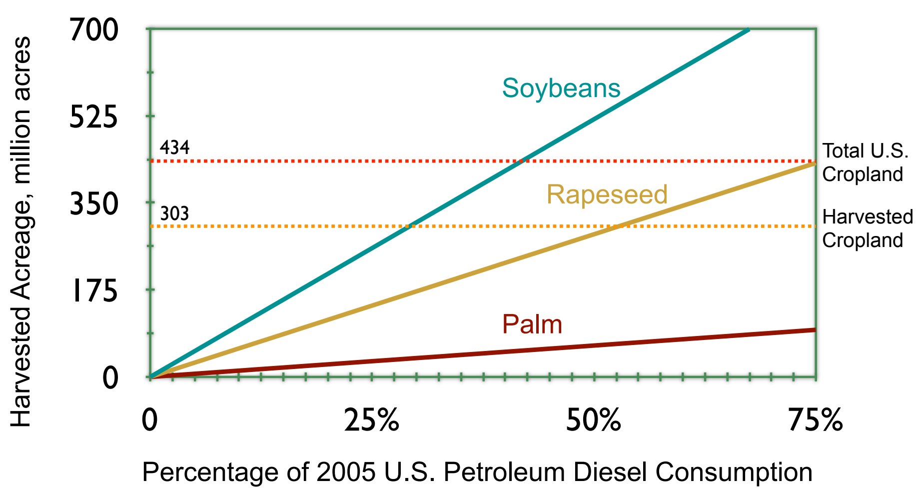
Land Required to Meet U.S. Diesel Needs with Biodiesel



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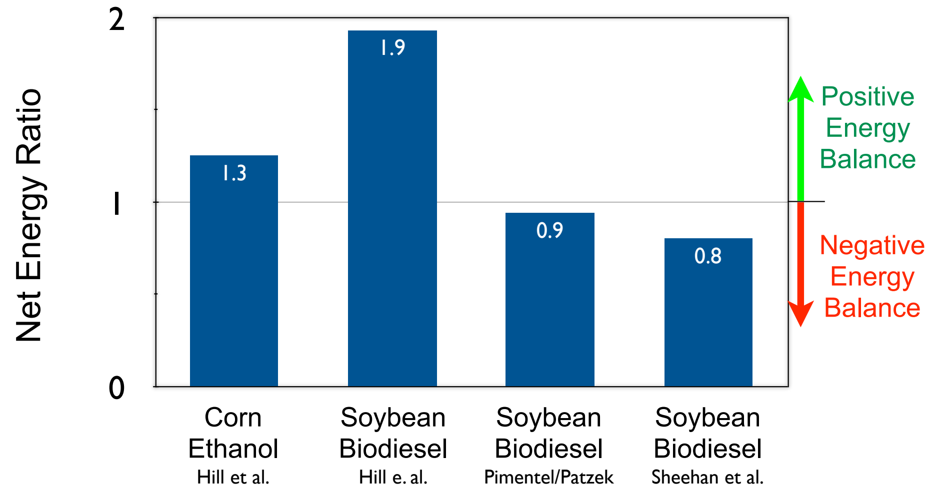
Energy Balance for Biodiesel



Hill et al., PNAS, **103**, 11206-11210 (2006)

Pimentel and Patzek, NRR, **14**, 65-76 (2005)

Sheehan et al., NREL Report TP-580-24772 (1998)

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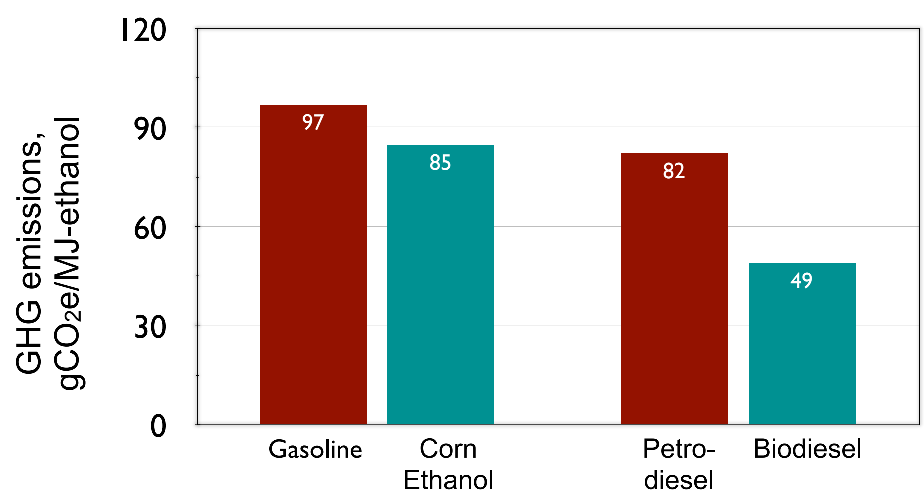
GHG Emissions for Biodiesel



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Carbon Debt from Land Use Change

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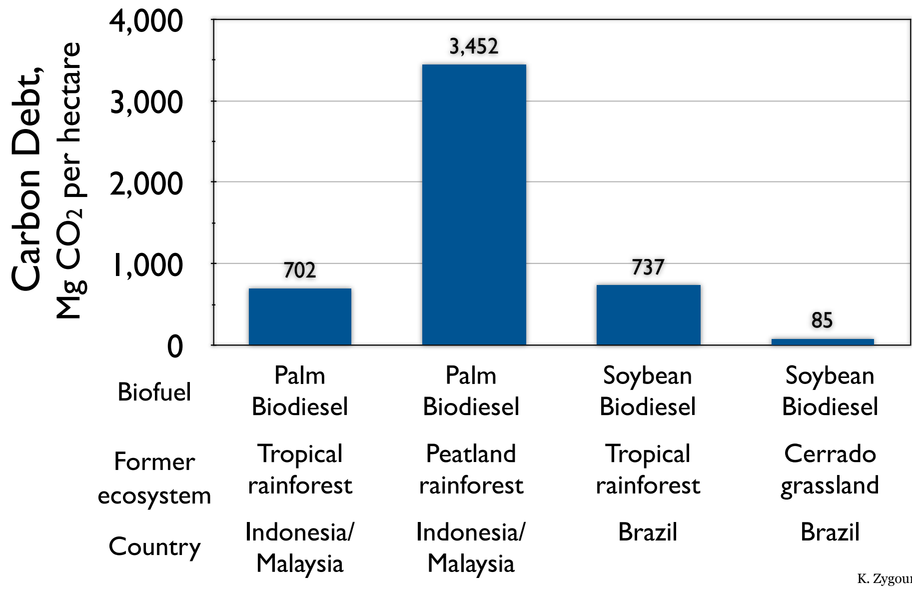

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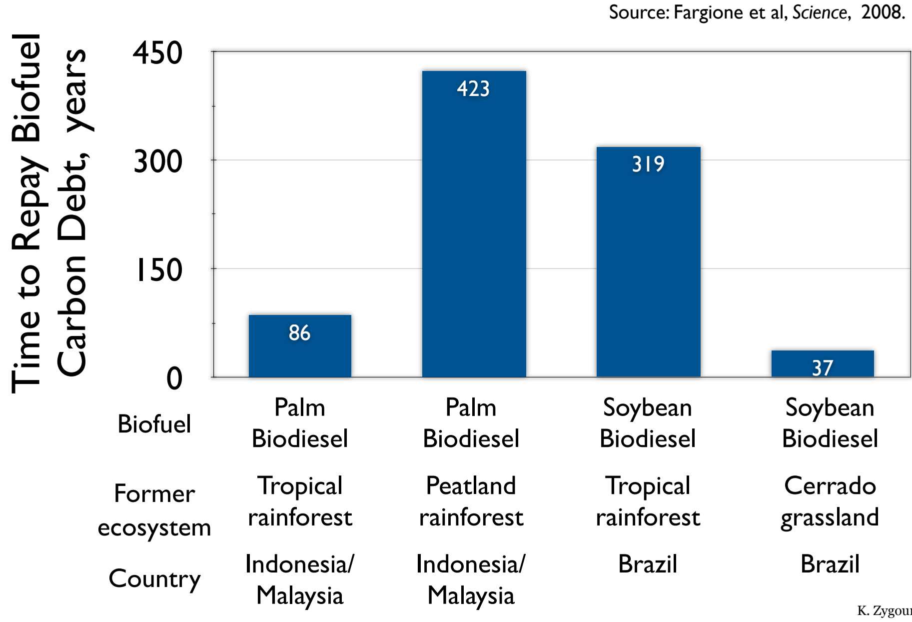

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Biodiesel vs. Cellulosic Ethanol

	Cellulosic Ethanol	Biodiesel
Technology	Under development Large capital investment	Here now Low capital investment
Yield (gallons / acre)	High	Low
Small Scale?	No (??)	Yes

Concluding Remarks

- Both corn ethanol and biodiesel can only meet a small fraction of the U.S. needs for liquid transportation fuels.
- GHG emissions from corn ethanol are similar to those of gasoline and its energy balance is marginal at best.
- GHG emissions from biodiesel are lower than petro-diesel and it can be easily produced and deployed locally. But, there is still some uncertainty about its energy balance.

Concluding Remarks

- Significant uncertainties still remain about cellulosic ethanol. Major technical challenges lie ahead, large land areas will be required to meet a significant fraction of U.S. demand for liquid transportation fuels and its energy balance may not be as favorable as claimed by proponents.
- Converting rainforests, peatlands, savannas or grasslands to produce biofuels creates a large biofuel carbon debt that may take up to hundreds of years to repay with the GHG reductions obtained when biofuels displace fossil fuels.