



CARNEGIE  
INSTITUTION FOR  
SCIENCE

DEPARTMENT OF  
GLOBAL ECOLOGY



Stanford University  
**Global Climate & Energy Project**

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# Biomass Energy: the Climate Protective Domain

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# Constraints

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Food  Fuel

Fossil offsets  Other emissions

Energy  Nature

# Climate-protective biofuels

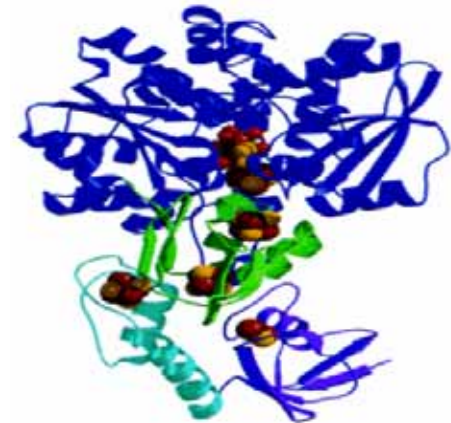
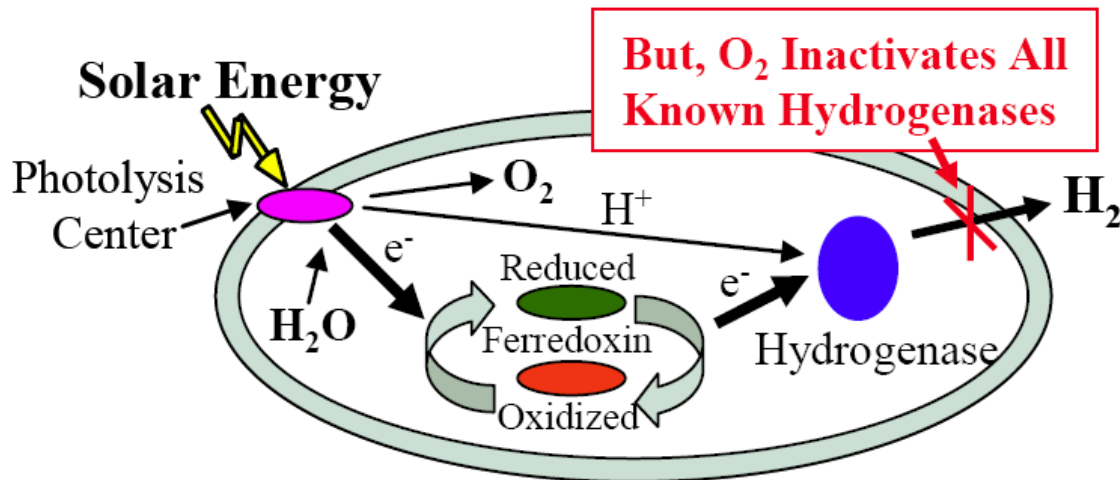
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- Grow more plants
  - Without more environmental downsides
- Get more energy per unit of plant biomass
- Figure out where it does and doesn't make sense to produce biofuels

# Direct Solar Biohydrogen

Jim Swartz

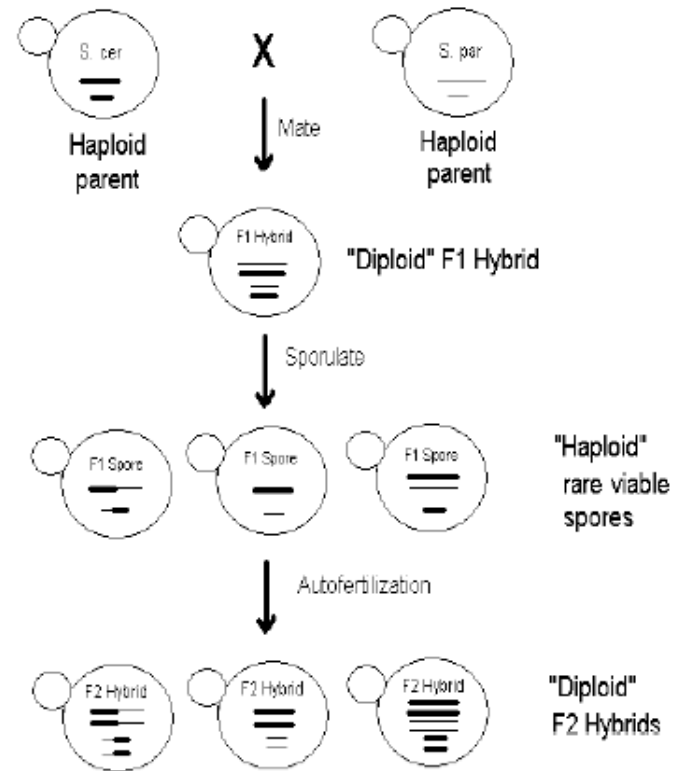
- Engineer *Synechocystis* organism to demonstrate photobiological production of hydrogen
- Modify protein structure of hydrogenase enzyme to exclude oxygen from active site while still allowing protons to enter and hydrogen to exit
- Use a cell-free protein evolution approach to:
  - Express and activate hydrogenase enzyme
  - Produce an uncoupler protein to aid flow of protons
  - Optimize organism for resistance to light exposure and to infection
- Test hydrogen production in photobioreactor set-up.



# Directed Evolution of Novel Yeast Species

Gavin Sherlock, Frank Rosenzweig

- Improve the efficiency and flexibility of biomass conversion through development of novel, adaptively evolved, hybrid yeast strains.
  - *Saccharomyces cerevisiae* is able to ferment the hexose sugars in cellulose to ethanol
  - Evolve the organism to also include the ability to produce ethanol by the fermentation of pentose sugars, xylose and L-arabinose, present in hemicellulose
- Allows use of all of the substrate found in cellulosic and hemicellulosic feedstocks



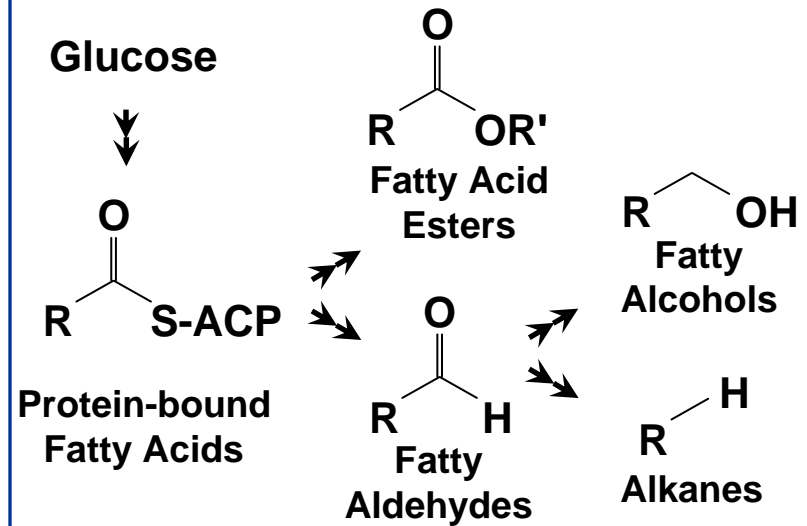
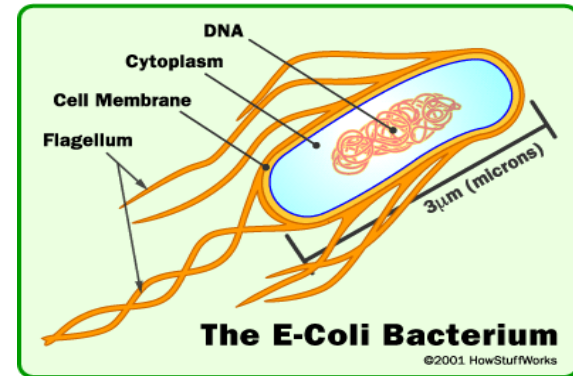
Process to create hybrid yeast species

# Microbial Synthesis of Biodiesel

## Chaitan Khosla

Engineer *E. coli* as a microbial factory for production of fatty acids:

- Increase carbon flux (acetyl-CoA) to fatty acid biosynthesis synthesis (malonyl-CoA) by expressing genes from two key control enzymes
- Biosynthesize fatty acid alternatives (e.g. aldehydes, esters and lactones), using existing fatty acid pathways and heterologous enzymes, and evaluate their quality and potential as biodiesel fuels
- Co-express plant oleosin genes to accumulate higher concentrations of fatty acids



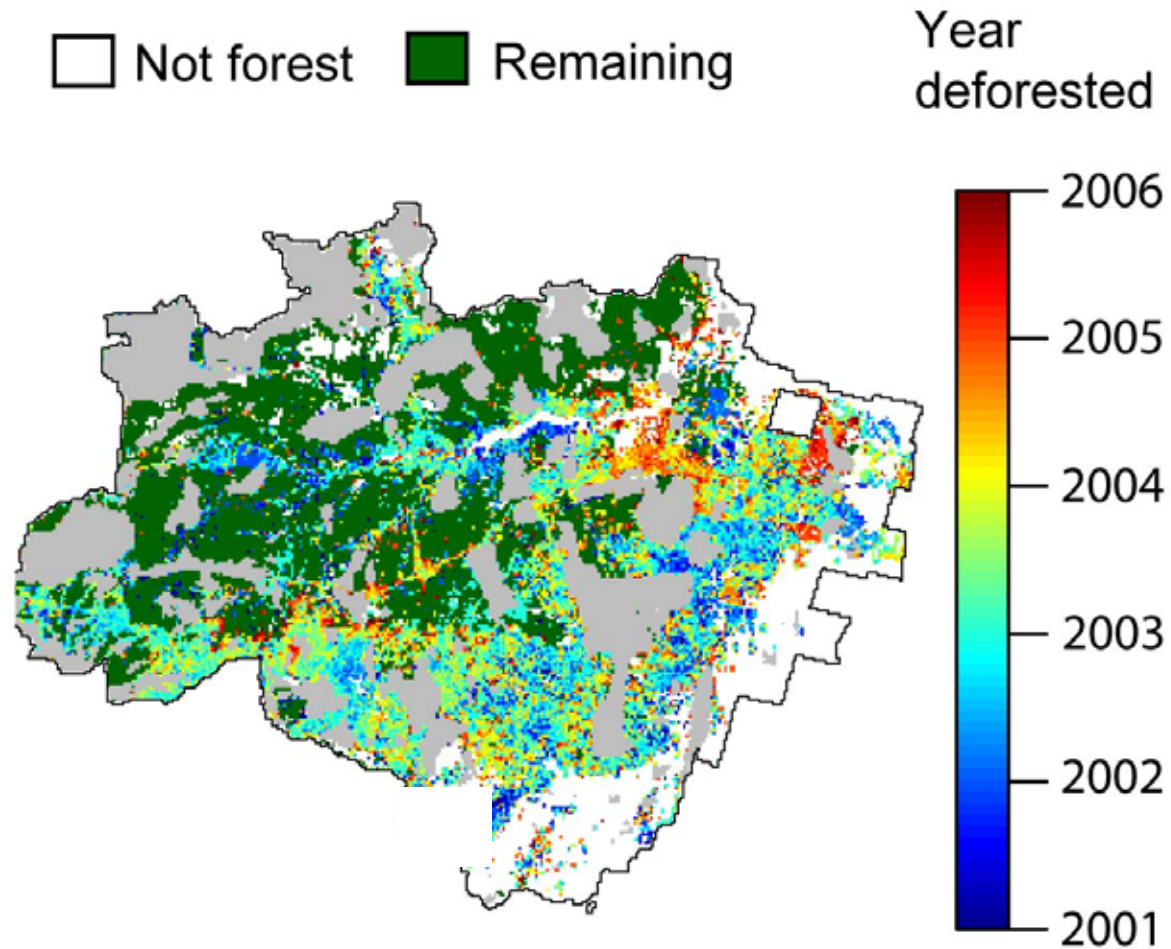
- Direct biodiesel production from biomass feedstock using engineered microorganisms could have both a potentially high yield and the high energy density of a hydrocarbon

# Biomass energy: the climate protective domain

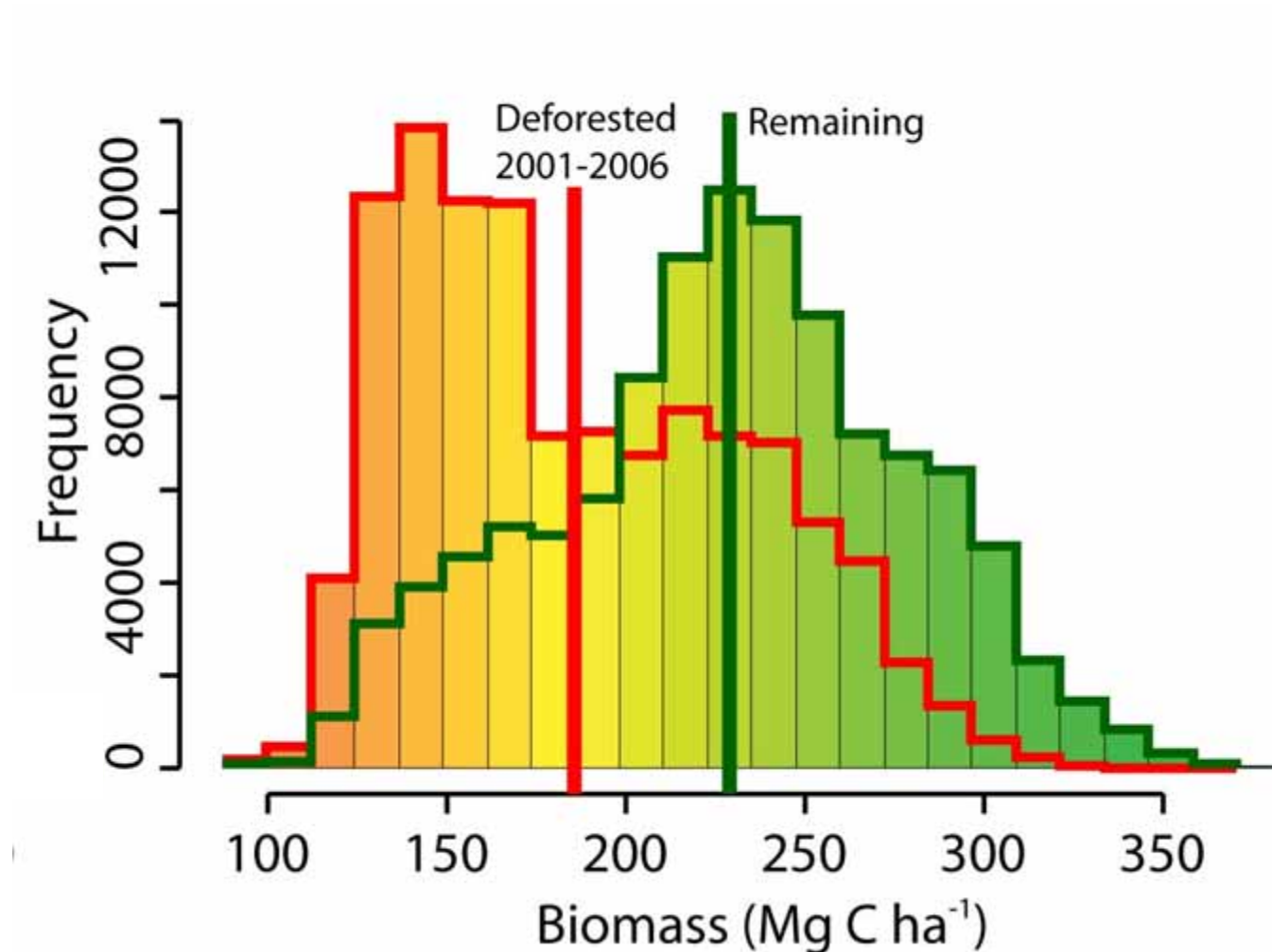
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- Food/Biomass energy interactions
  - Roz Naylor, Holly Gibbs
- Biomass in areas converted to bioenergy
  - Greg Asner, Scott Loarie
- Albedo feedbacks from bioenergy agriculture
  - David Lobell, Matt Georgescu
- Available land, potential yield, GHG balance
  - Chris Field, Elliott Campbell

# Year-by-year deforestation

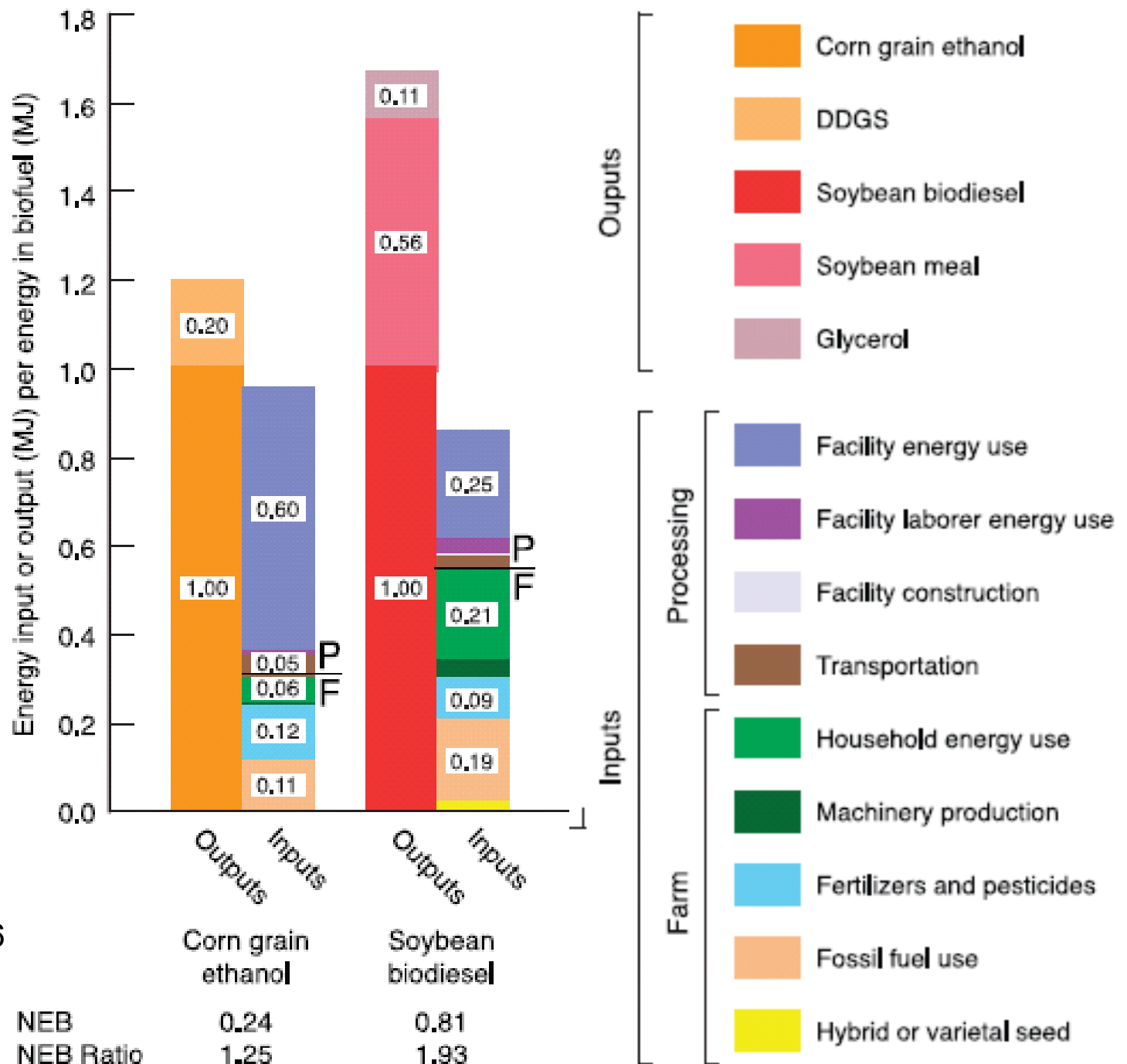


# Greater biomass in remaining forests



# Setting the scale

- Food for 1 person for one year
  - ~ 250 kg corn
- = ethanol for one fill-up
  - ~ 80 l (20 gal)
- At 25 mpg and 10,000 miles/y
  - The corn required to fuel one car on corn ethanol
  - Would feed 20 people
  - Would require 1 Ha of farmland



Hill et al PNAS 2006

NEB	0.24	0.81
NEB Ratio	1.25	1.93

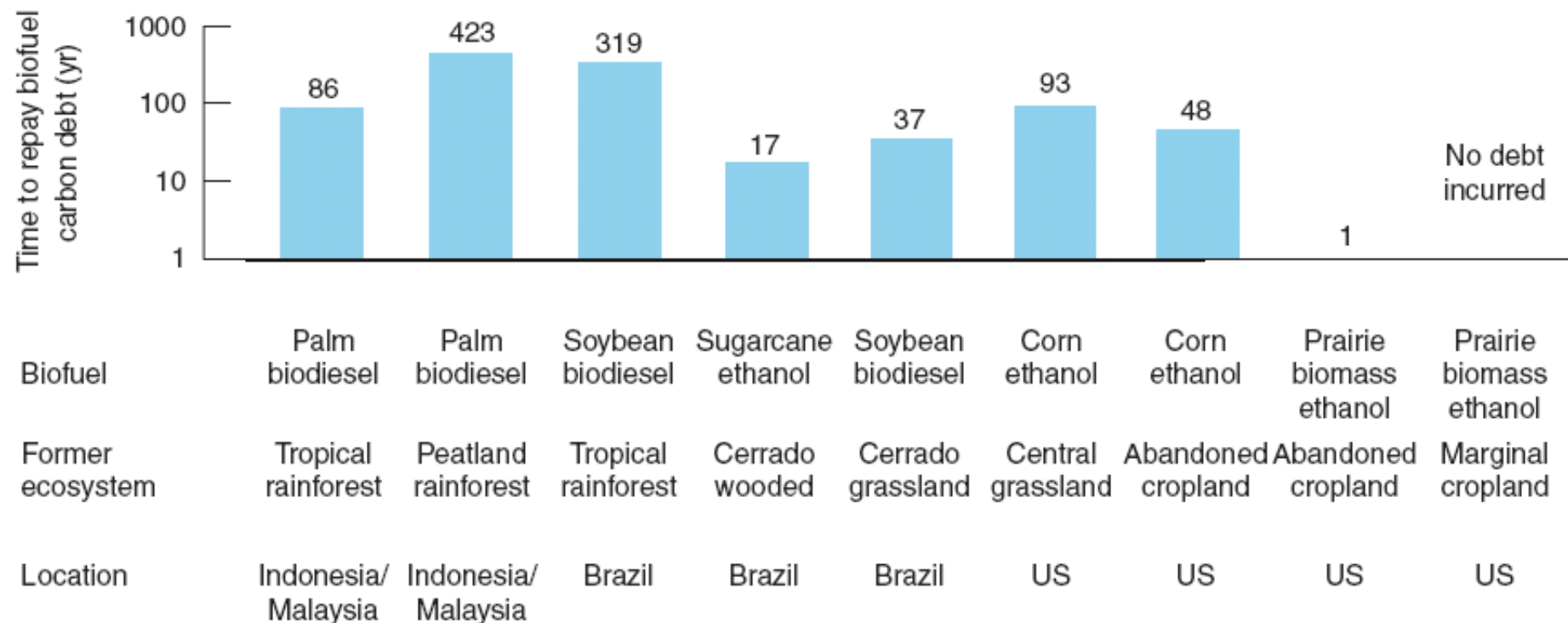
# Net energy balance ratio

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(biomass energy out/fossil energy in)

- Corn ethanol ~1.2
- Sugarcane ethanol ~ 8
- Soy biodiesel ~ 2
- Palm biodiesel ~ 9
  
- Cellulosic ~5(?)

# Carbon “debt” from expanding agriculture



# Energy in ag and pastures?

Land Type		Area (Mha)	Mean NPP (ton C/ha/y)	Total NPP (Pg C/y)	Total Energy* (EJ/y)
Global	Crop	1,445	4.6	6.7	119
	Pasture	3,321	3.4	11.3	200
US	Crop	173	5.7	1.0	18
	Pasture	226	3.5	0.8	14

Global Primary Energy = 480 EJ/y

\* In ½ biomass (to allow for roots), assume 45% C

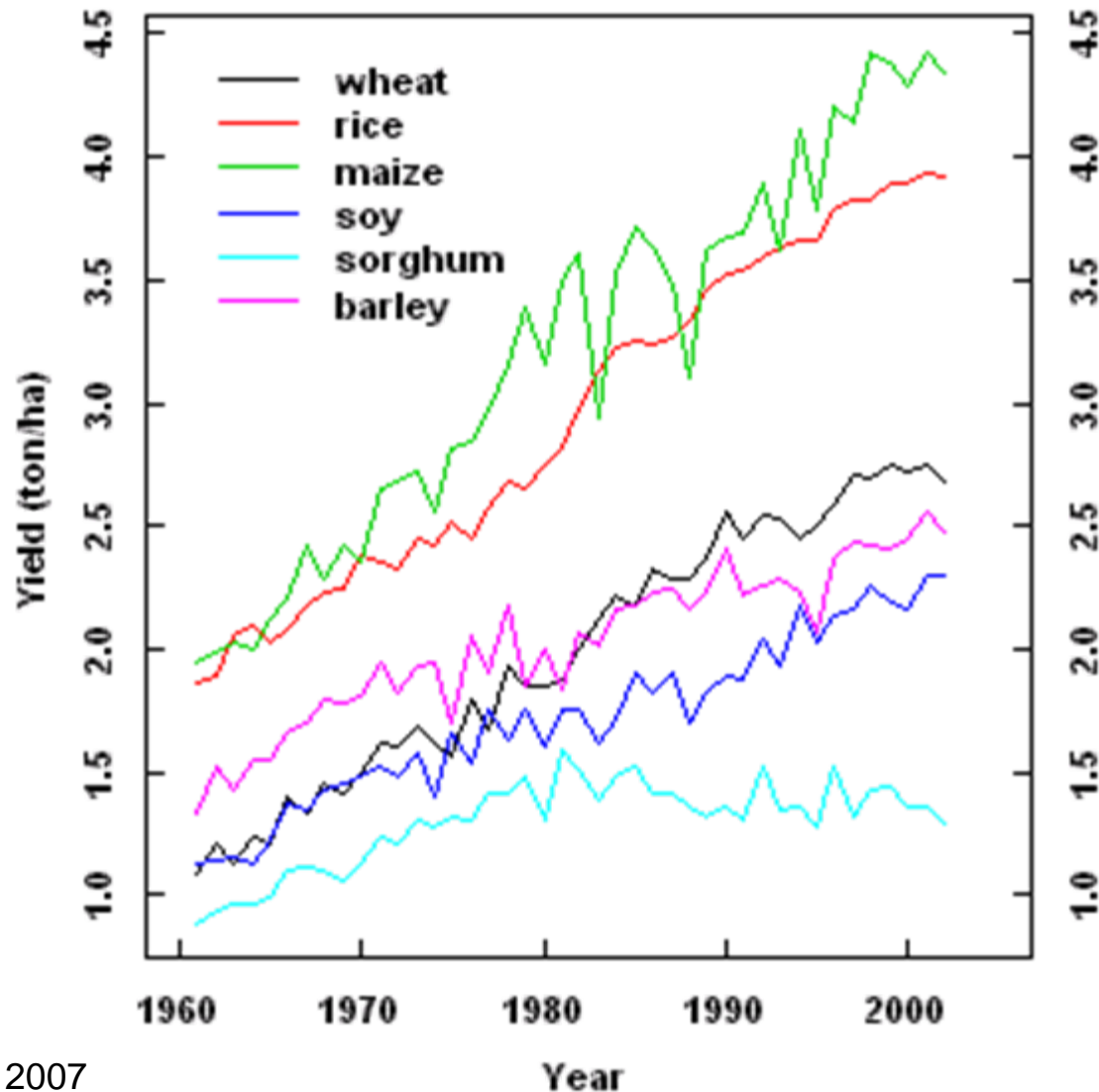
# Will yields increase dramatically?

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- Historical trends – a century of success
  - 1-2%/y for major crops
- Will this continue?
  - Can it accelerate?

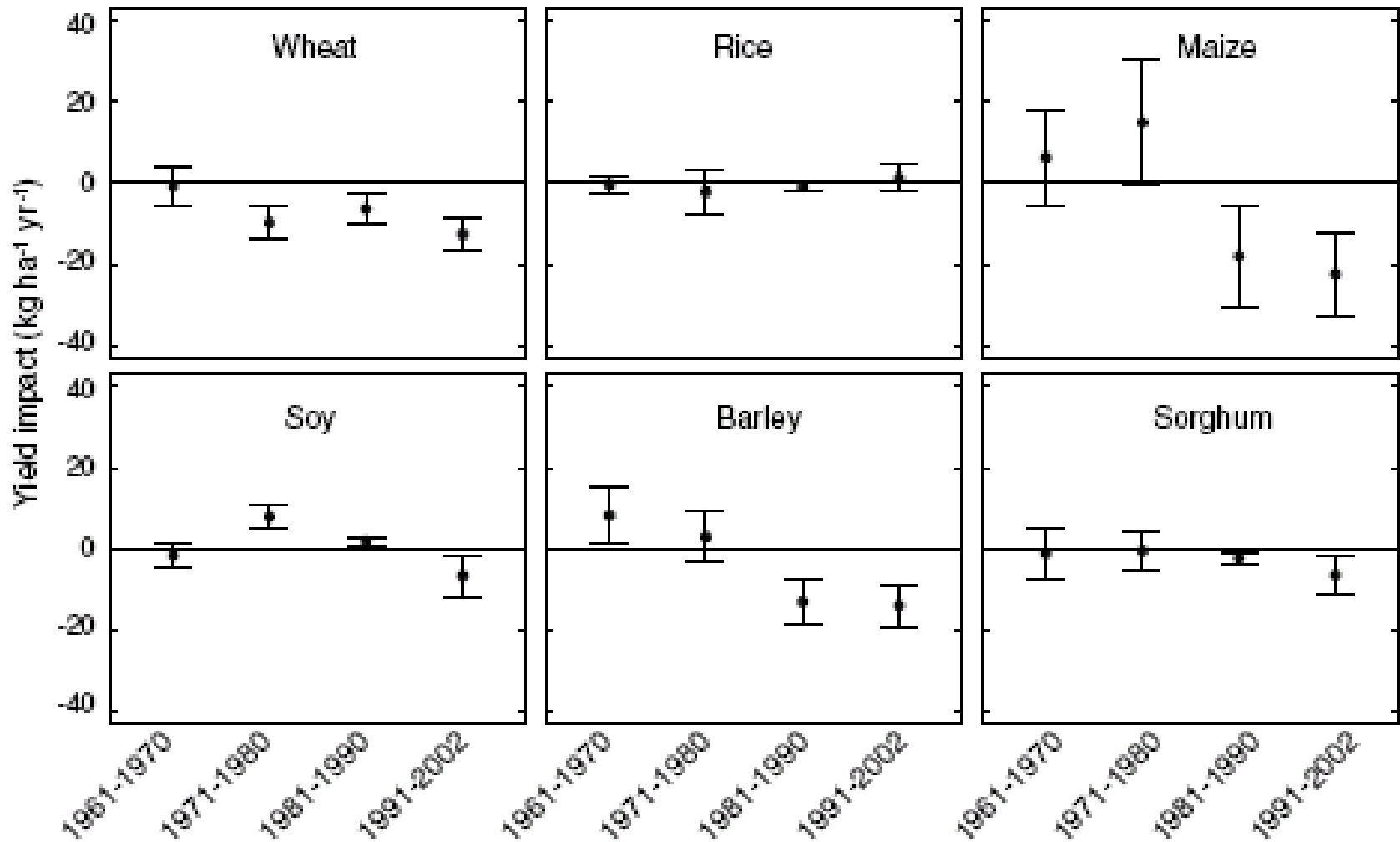
# Ag yields – a century of success

increases of 1-2%  $y^{-1}$



# Extracting climate sensitivity

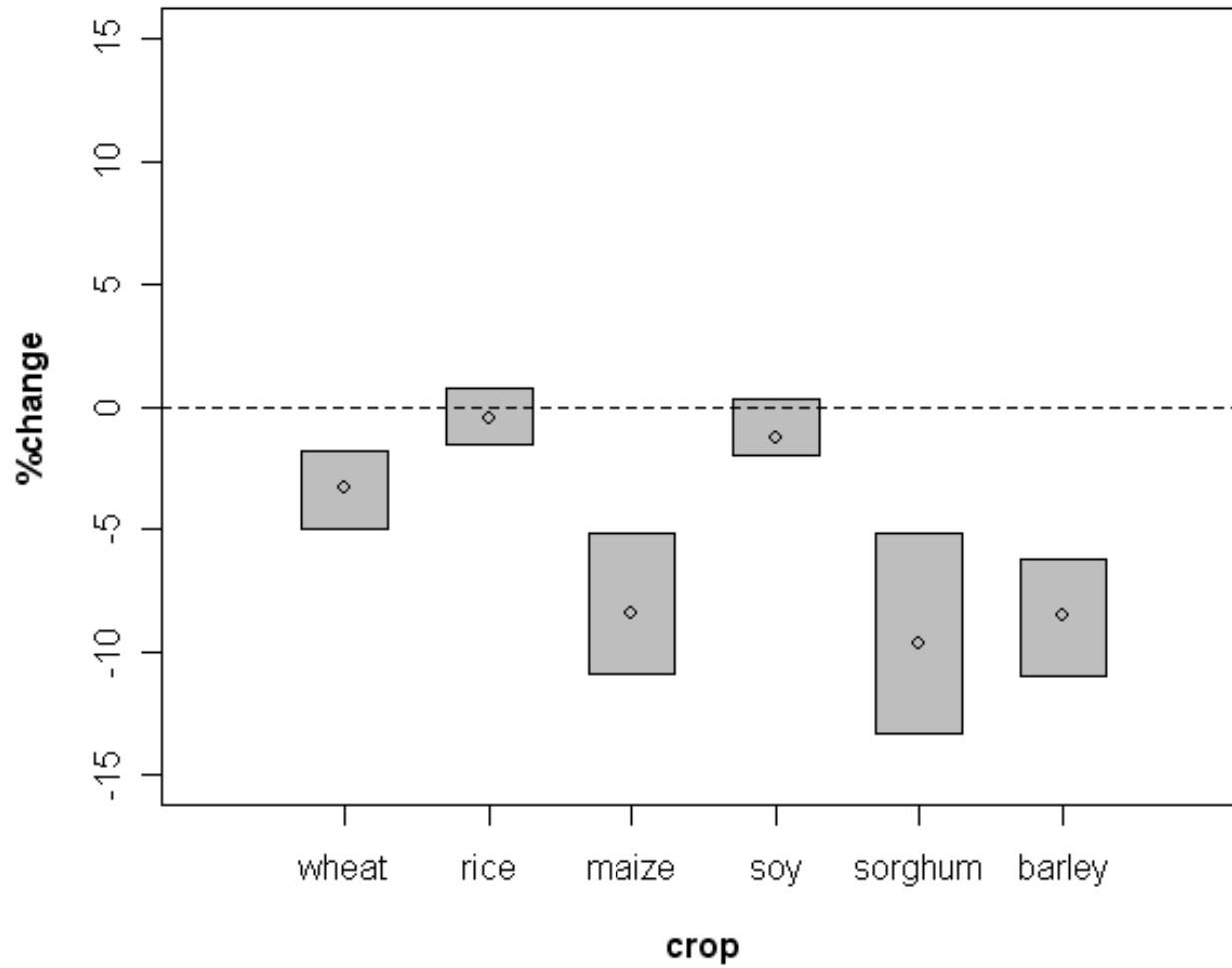
- First difference yield
- Define locally-weighted climate
- Regress against
  - Growing season  $t_{\max}$ ,  $t_{\min}$ , precip
  - Define growing season based on explained variance
- Reconstruct trend with (observed) and without (climate corrected) climate



# Global area, production, and yield changes for six major world crops

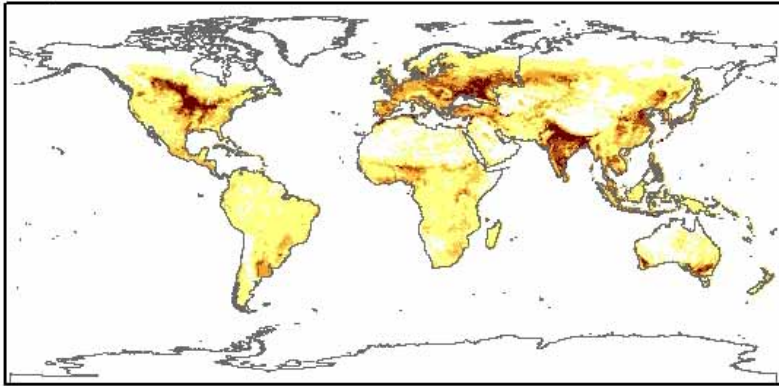
	Wheat	rice	maize	barley	soybean	sorghum
2002 Area (Mha)	214	148	139	55	79	42
2002 Production (Mt yr <sup>-1</sup> )	574	578	602	137	181	54
Yield change, 1981-2002 (kg/ha)	846	1109	1178	473	632	-80
Climate driven yield change, 1981-2002 (kg/ha)	-60.1	-6.5	-89.5	-140.3	23.1	-20.0
Climate driven production change, 1981-2002 (Mt yr <sup>-1</sup> )	-12.9	-1.0	-12.4	-7.8	1.8	-0.8

### yield response to +1 C

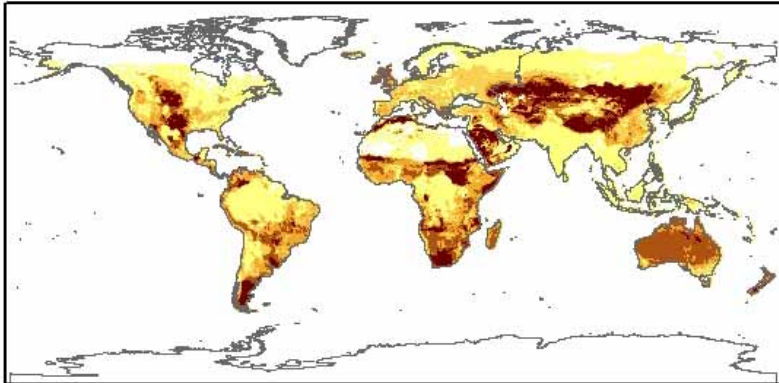


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- Ag in relation to natural NPP
    - Ag/NPP -- Globally about 65%
  - Global average crop yields unlikely to exceed natural NPP for at least the next several decades

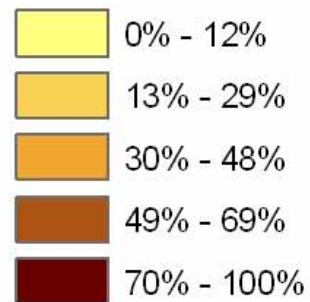
a) Crop



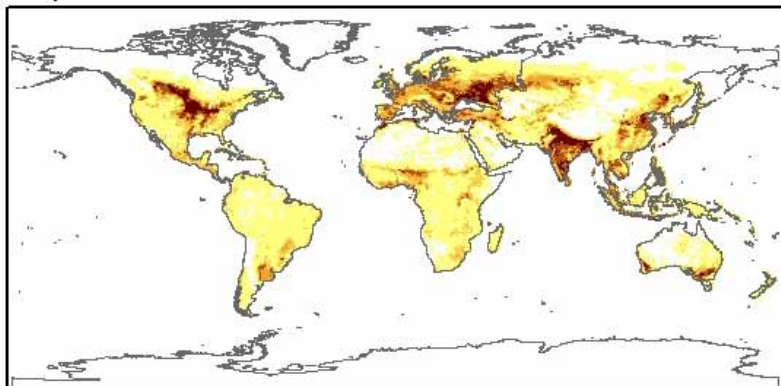
c) Pasture



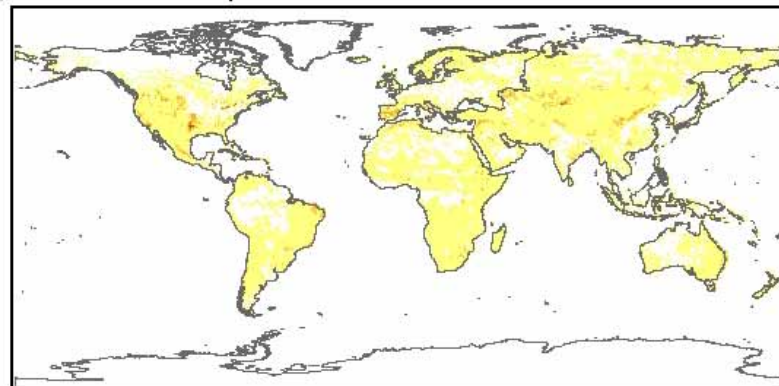
**Area (%)**



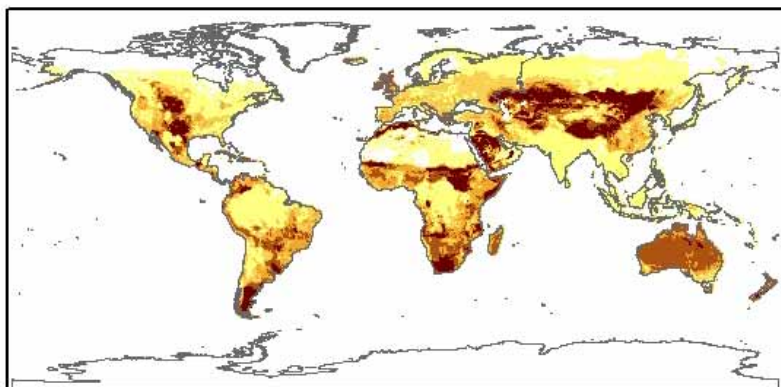
a) Crop



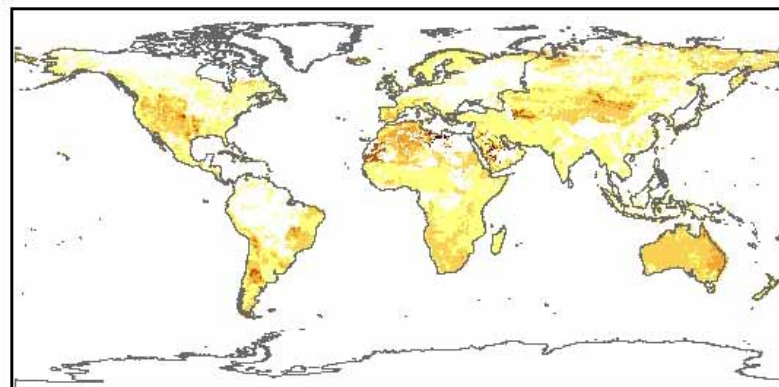
b) Abandoned Crop



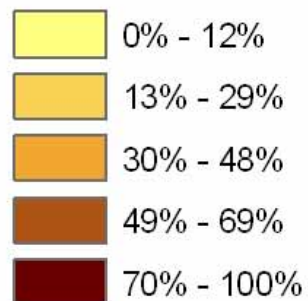
c) Pasture



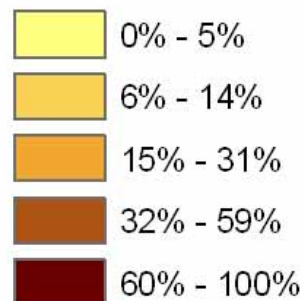
d) Abandoned Pasture



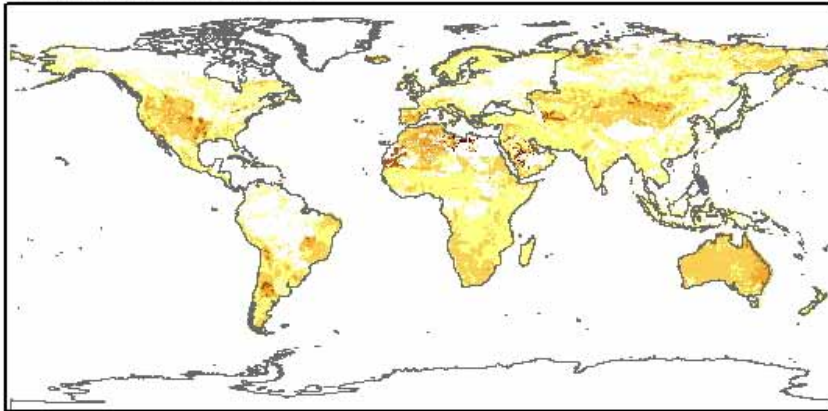
**Area (%)**



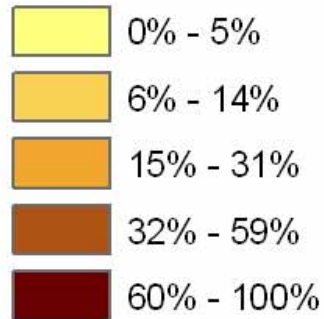
**Abandoned Area (%)**



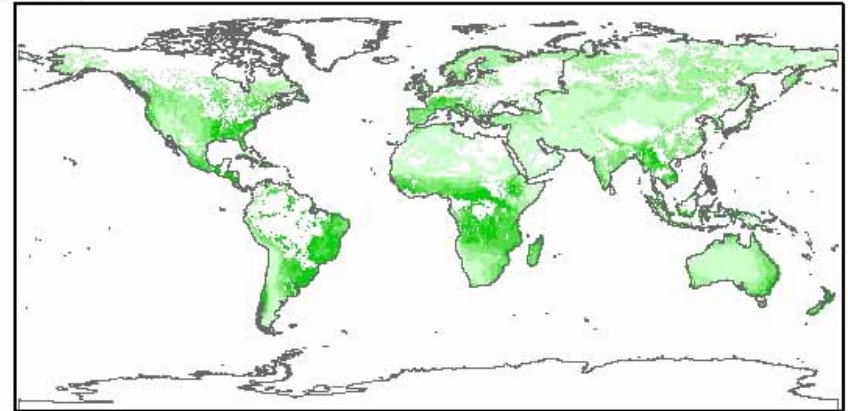
a) Total Abandoned Area



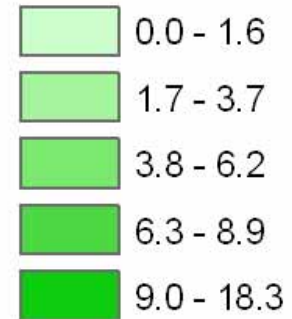
**Area (%)**



b) NPP



**NPP (Mg C / ha)**



# Potential from abandoned land

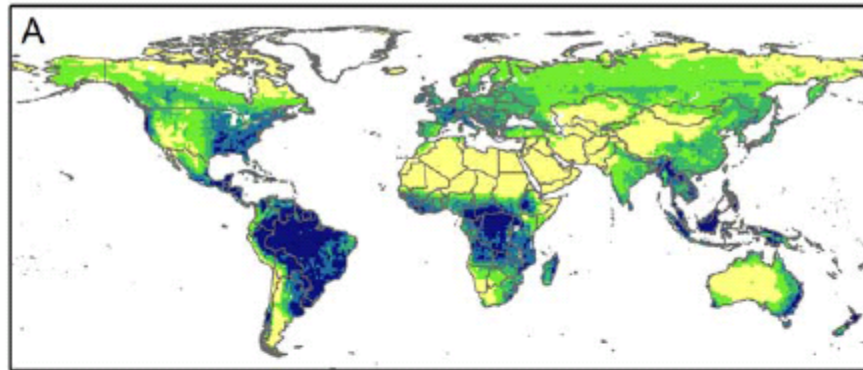
Land Type	Area (Mha)	Mean NPP (ton C / ha / yr)	Total NPP (Pg C / yr)
Global			
Crop	1,445	4.6	6.7
Pasture	3,321	3.4	11.3
Abandoned	474-579	4.7	2.2-2.7

# From available abandoned land

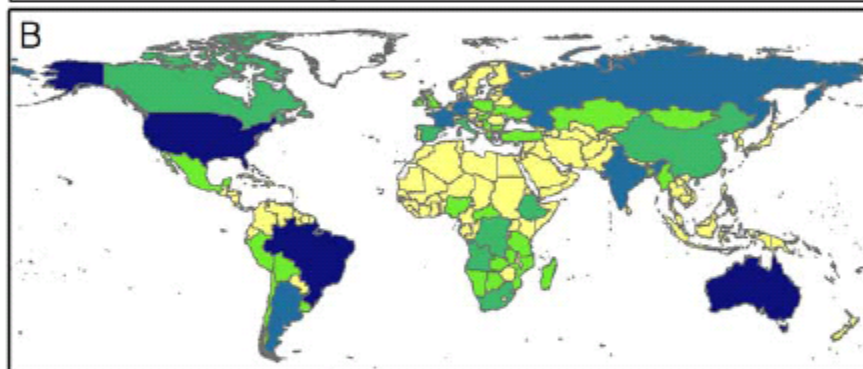
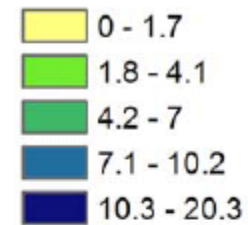
Land Type		Area (Mha)	Mean NPP (ton C / ha / yr)	Total NPP (Pg C / yr)
Global	Crop	1,445	4.6	6.7
	Pasture	3,321	3.4	11.3
	Abandoned	474-579	4.7	2.2-2.7
	In Forest	72	6.5	0.5
	In Urban	18	5.0	0.1
	In Other	385-472	4.3	1.6-2.1

$1.6 - 2.1 \text{ Pg C} \times 2 \text{ g Plant/g C} \times 0.5 \text{ g top/g plant} \times 20 \text{ EJ/Pg} = 32 - 41 \text{ EJ}$

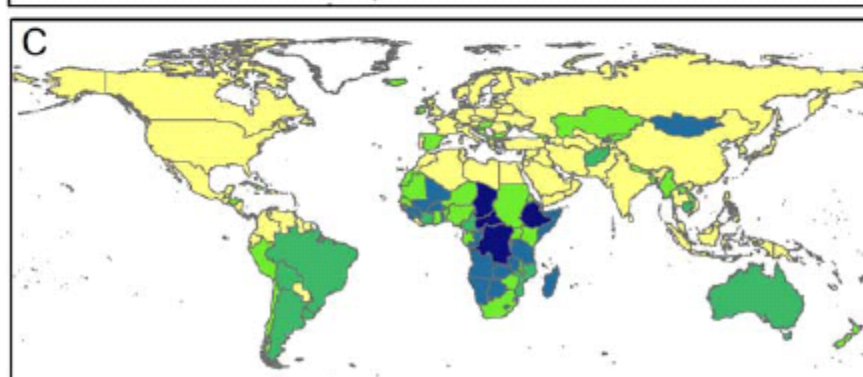
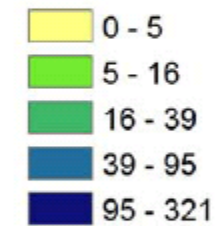
$= 7-8\%$  of current global energy system



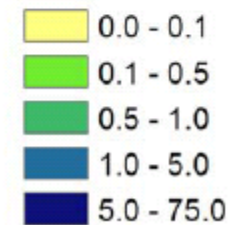
**Natural Production  
(ton ha<sup>-1</sup> y<sup>-1</sup>)**



**Potential Production on  
Abandoned Agriculture  
(million ton y<sup>-1</sup>)**

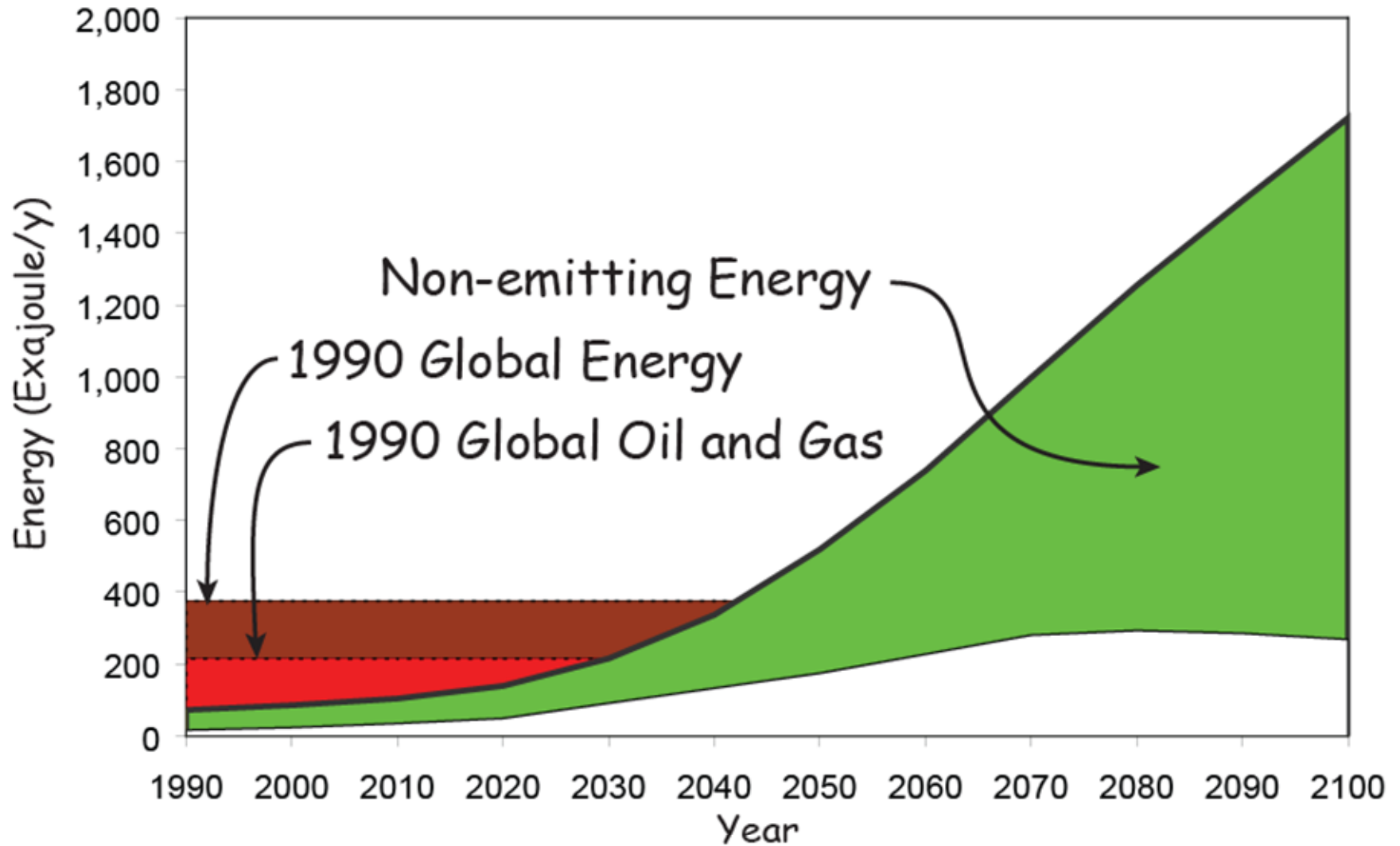


**Bioenergy : Primary Demand  
(EJ y<sup>-1</sup> : EJ y<sup>-1</sup>)**



- Climate impact depends on pre-existing ecosystem
- Indirect as well as direct paths to carbon loss
- Natural NPP reasonable proxy for potential yield under ag management
- Available land resource limited
  - Quantity and quality
- Big potential in absolute terms
- But a small slice of present or future demand

# Future energy needs: Many times current



# Biomass energy

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- Corn \$190/ton
- Coal      Power River      \$11/ton  
              Central Appalachia    \$140/ton
- Crude oil      \$730/ton

# Ferment or burn?

