Carbon Sequestration Opportunities with Biofuel Production

Jim Amonette
Ron Sands

Pacific Northwest National Laboratory

2007 Bio-based Industry Outlook Conference

Breakout Session: Climate Change Management in Biofuels Systems

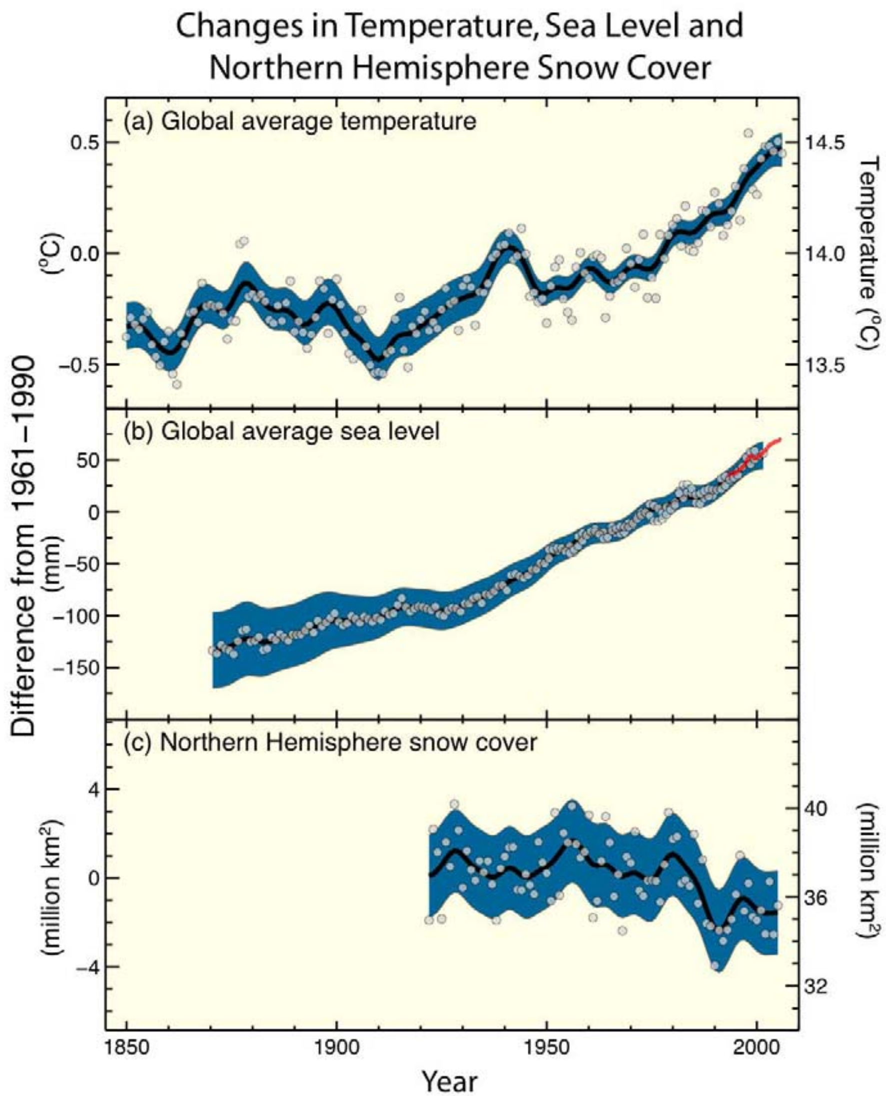
Iowa State University
6 November 2007

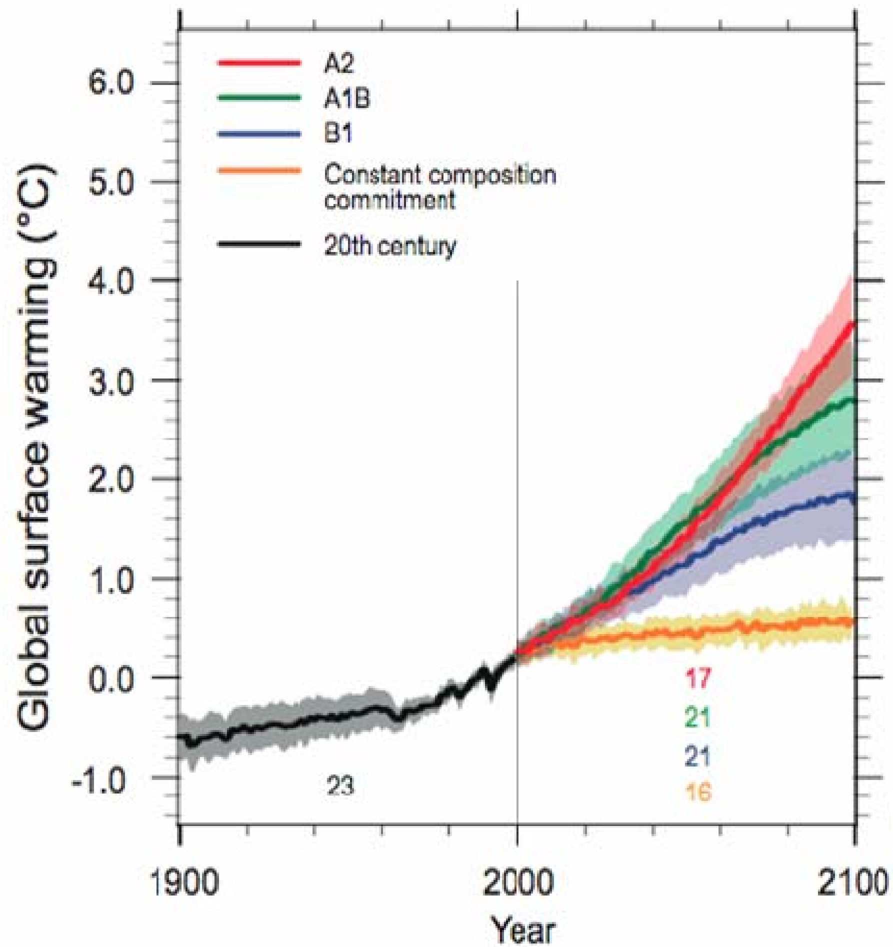
Pacific Northwest National Laboratory
Operated by Battelle for the U.S. Department of Energy

Outline

- Why we are here
  - Climate Change 101
- Carbon capture and storage approaches
  - Overview of geologic, oceanic, and terrestrial options
  - Opportunities for terrestrial C sequestration under biofuel production scenarios
    - Feedstocks
    - Conversion options
    - Resources and tradeoffs
    - Evolution of favorable options
- Summary

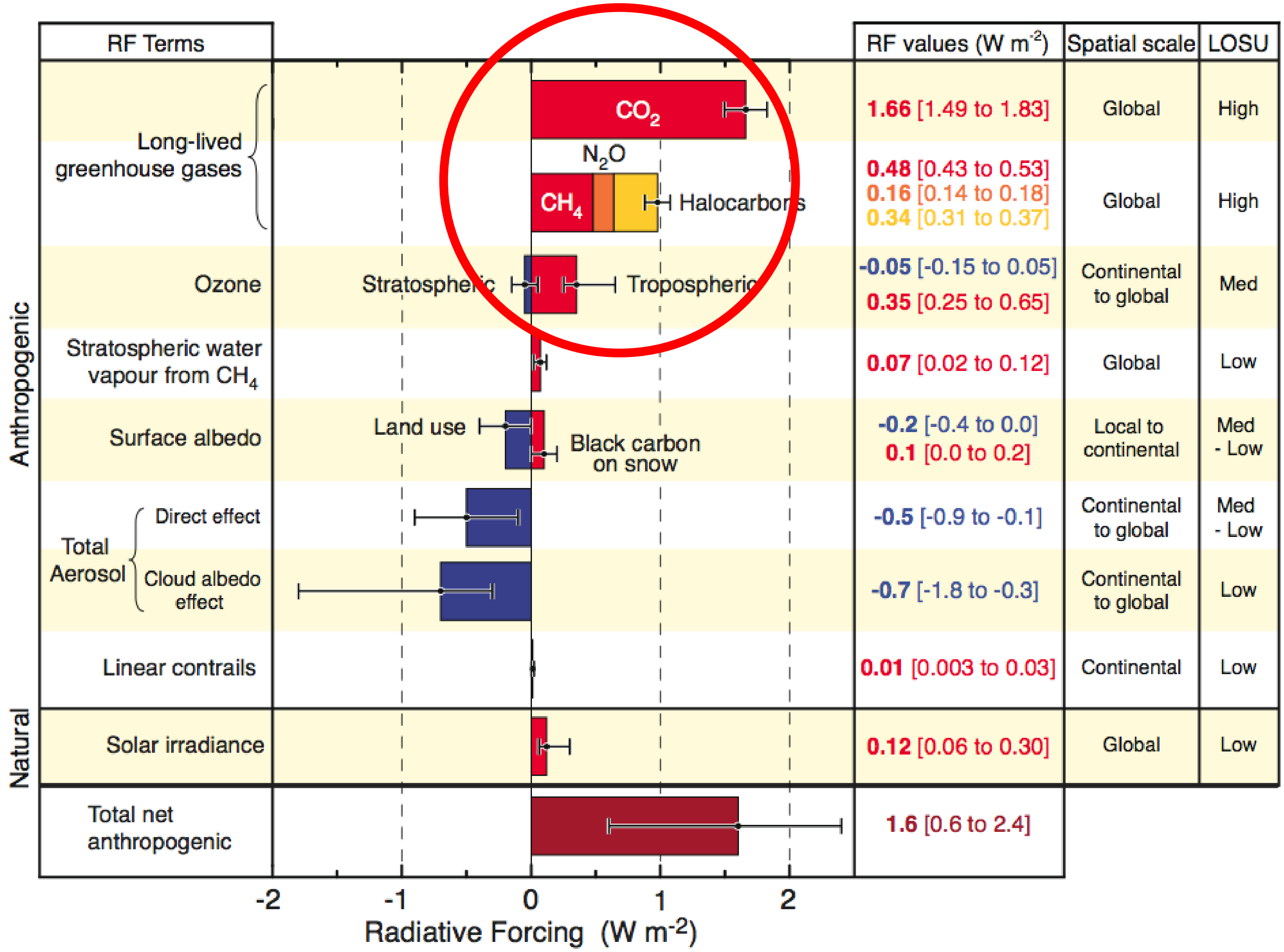
Observed and Projected Global Warming





IPCC (2007) WG1-AR4, SPM, p. 6, 14

Factors Affecting Global Warming (100-year timeframe)

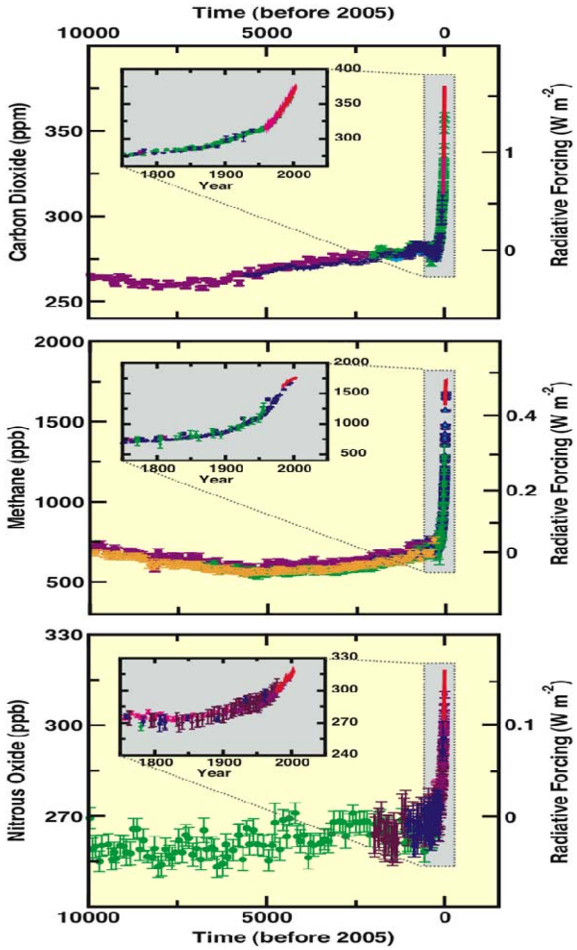


IPCC (2007) WG1-AR4, p. 136

Properties of Key Greenhouse Gases

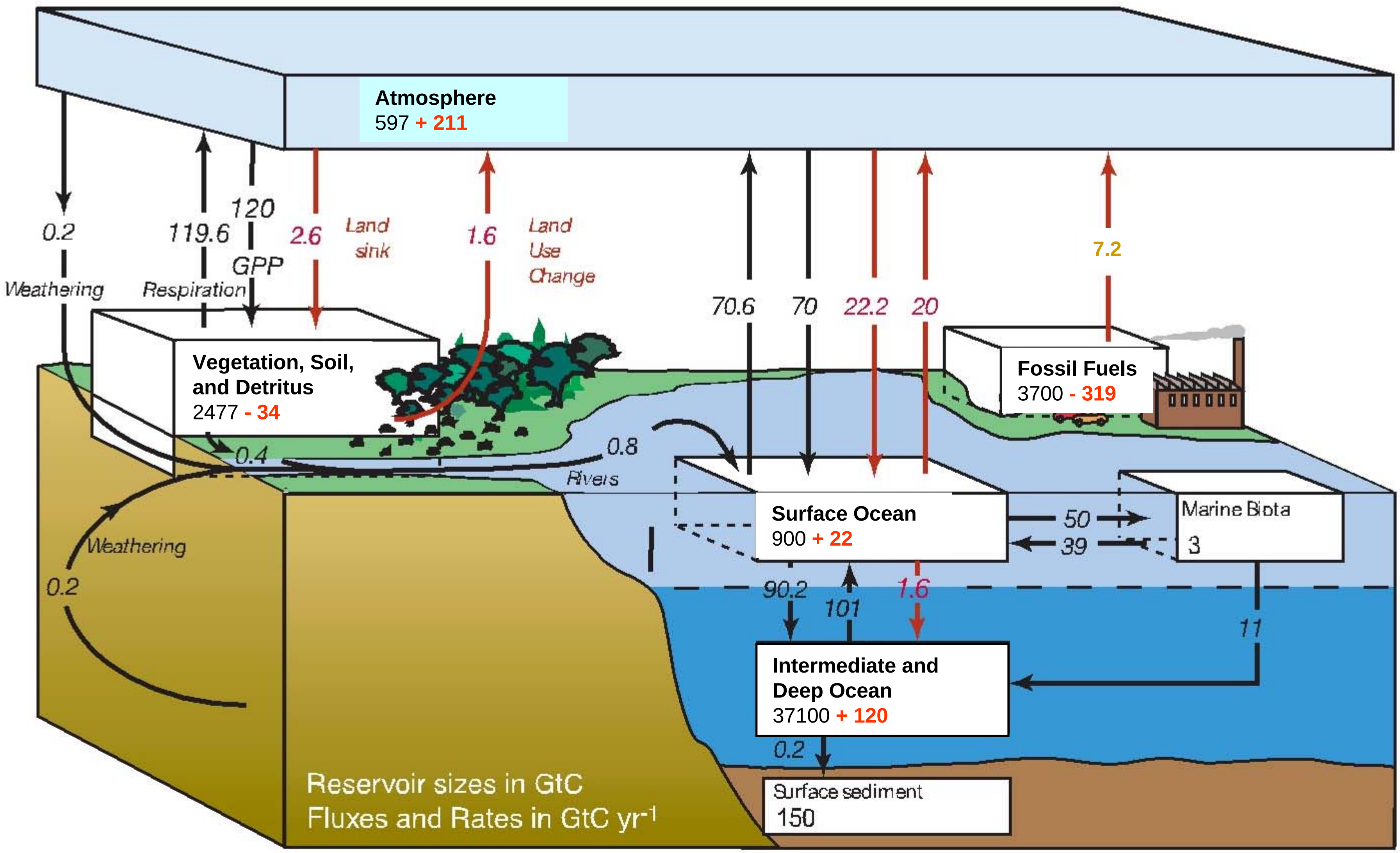
	Atmos. Half-life, yr	Relative Radiative Efficiency	Global Warming Potential (20-yr)	Global Warming Potential (100-yr)	Global Warming Potential (500-yr)
CO_2	30-325*	1	1	1	1
CH_4	8.3	26	72	25	7.6
N_2O	79	214	289	298	153
CFC-12	69	23000	11000	10900	5200
H_2O	~0.011	~0.4	Due to its short half-life (precipitation!), H_2O is a feedback gas, rather than forcing warming		

*Decay rate has several pathways with different rates. About 22% of the CO_2 is very long lived. The first two half-lives are 30 yr and 325 yr.



IPCC (2007) WG1-AR4, SPM, p. 3

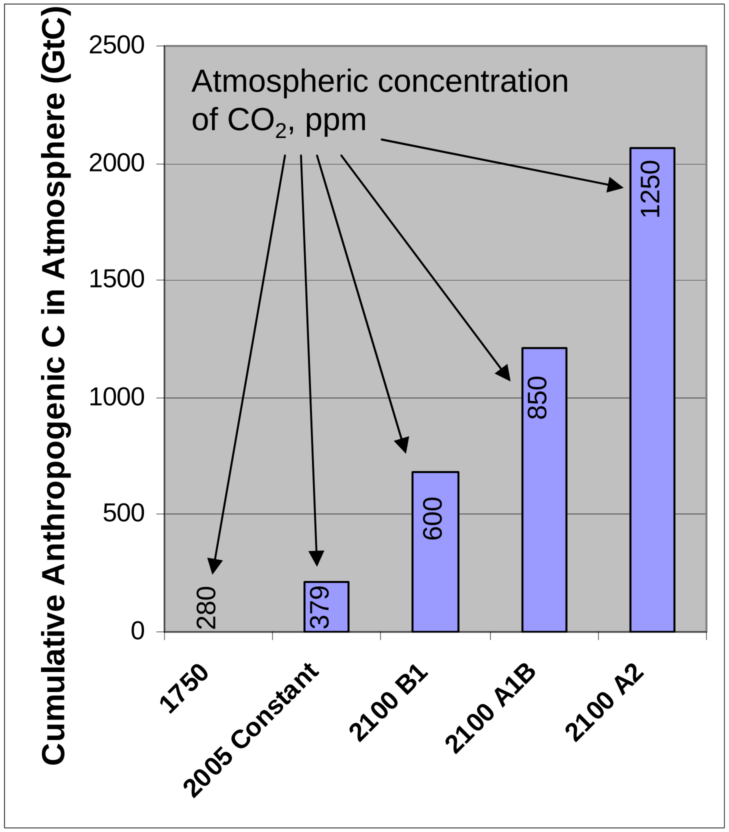
C Reservoirs and Transfer Rates

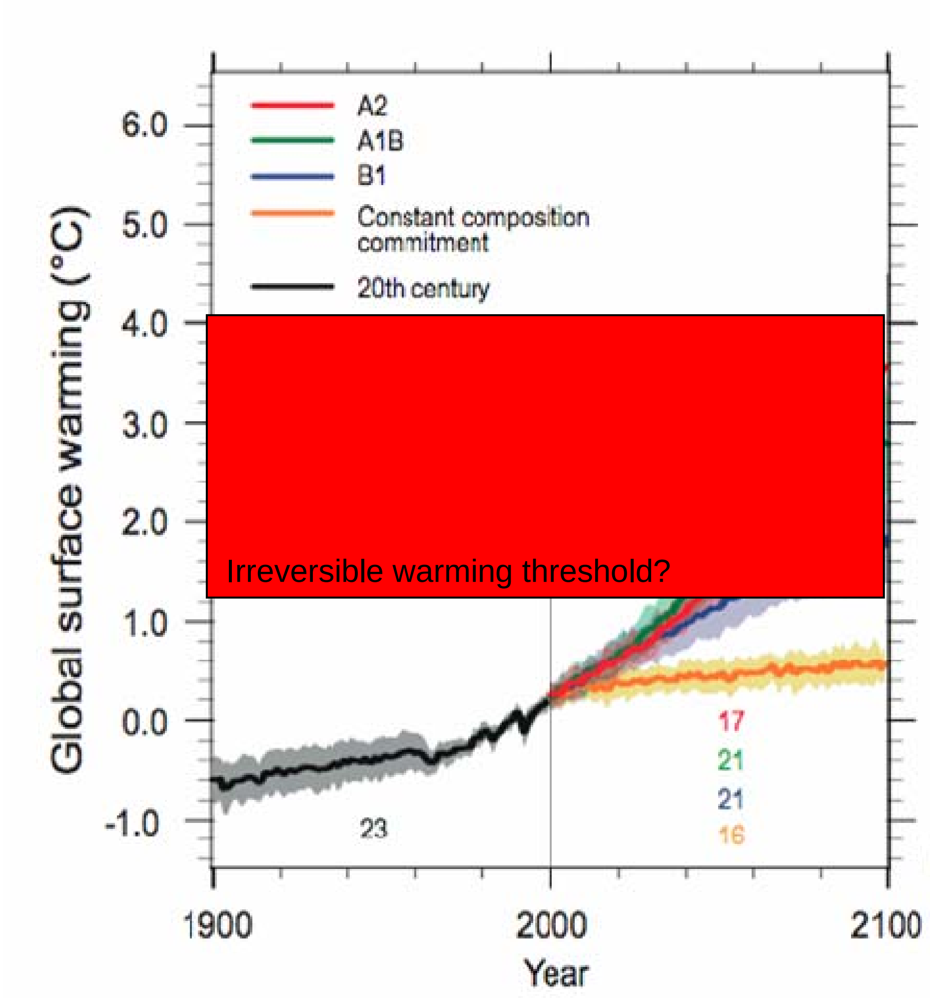


Pre-industrial values (1750)
Anthropogenic changes (2005)

Adapted from IPCC AR4 WGI with updated inventory and flux data

Projected Atmospheric Carbon Levels and Associated Global Warming



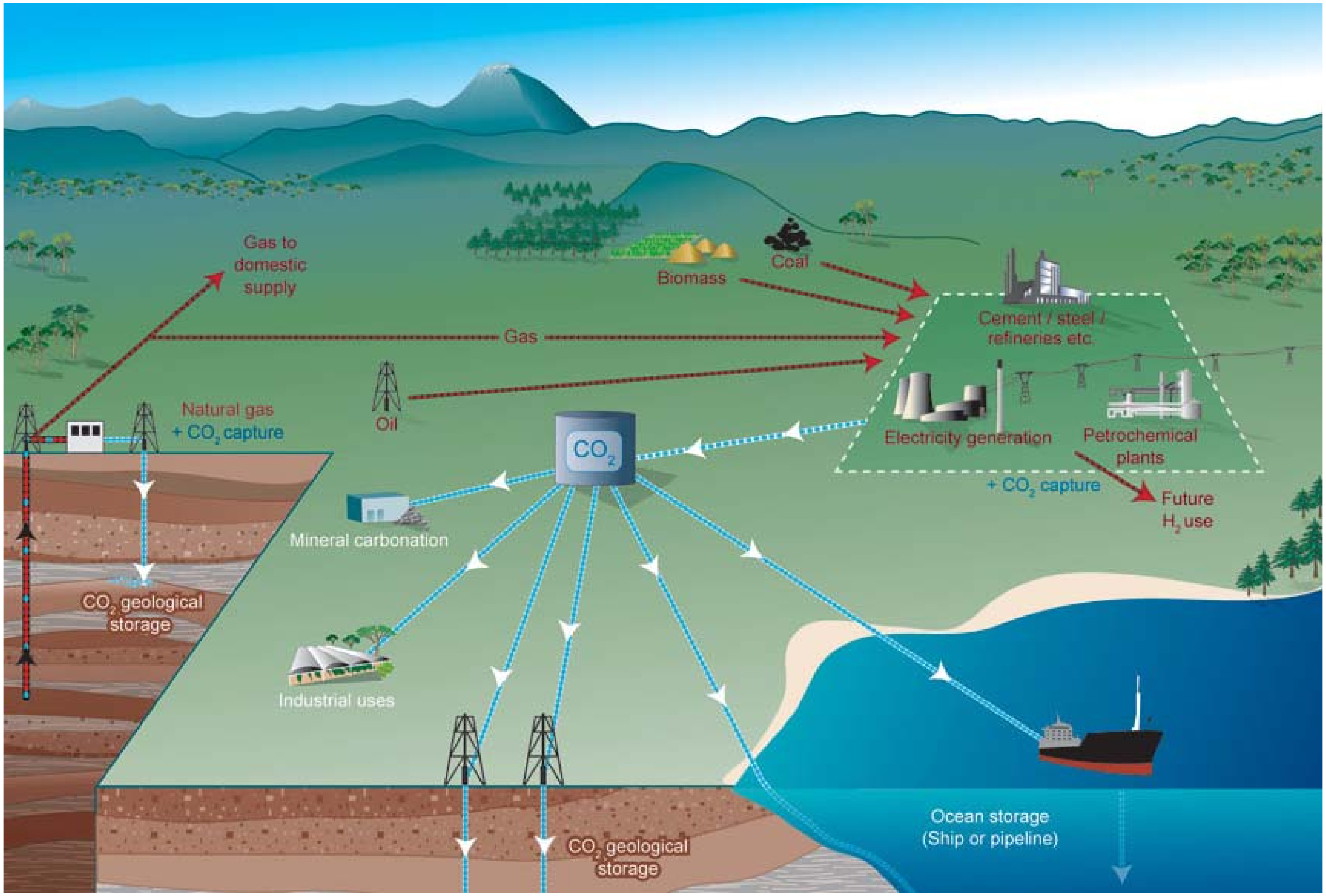


IPCC (2007) WG1-AR4, SPM, p. 14, modified to show zone where irreversible warming of Greenland ice sheet is projected to occur (ibid., p. 17)

What to do . . .

- Eliminate the C-positive, accentuate the C-negative!
- Minimize fossil fuel inputs
  - Improve energy efficiency
  - Point-source capture/sequestration of CO_2
  - Replace with biofuels, nuclear (???$$$)
- Maximize terrestrial sink (diffuse capture/sequestration)
  - Afforestation
  - Low-input and perennial cropping systems
- Implement C-negative energy technologies
  - Biomass combustion with CO_2 sequestration
  - Biomass pyrolysis with biochar production/CO_2 sequestration

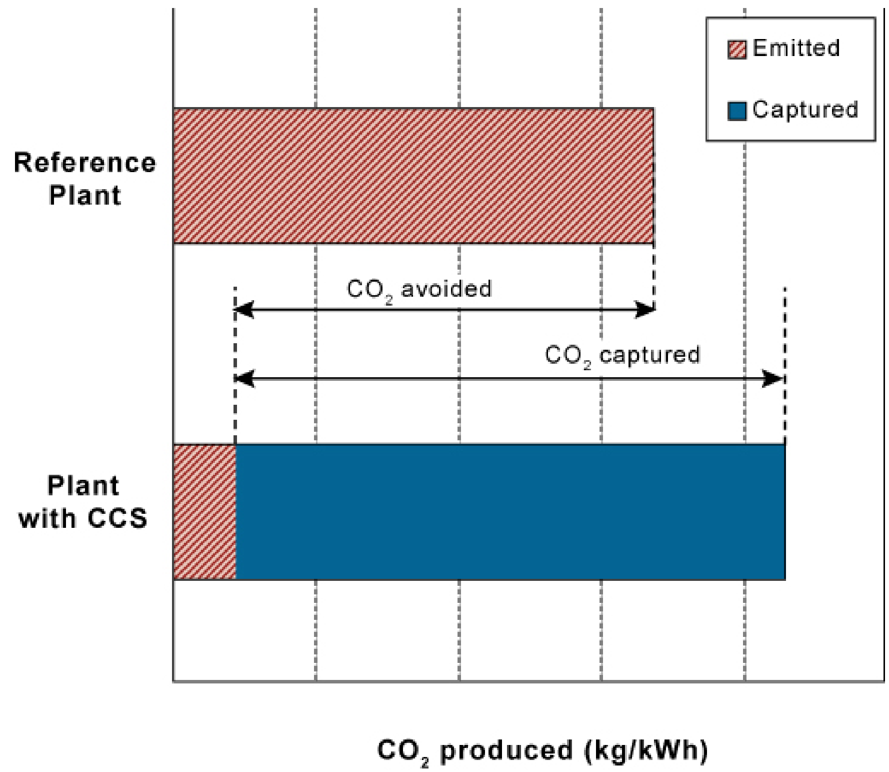
Point-Source CO_2 Capture and Storage



IPCC (2005) Special Report on CO2 Capture and Storage

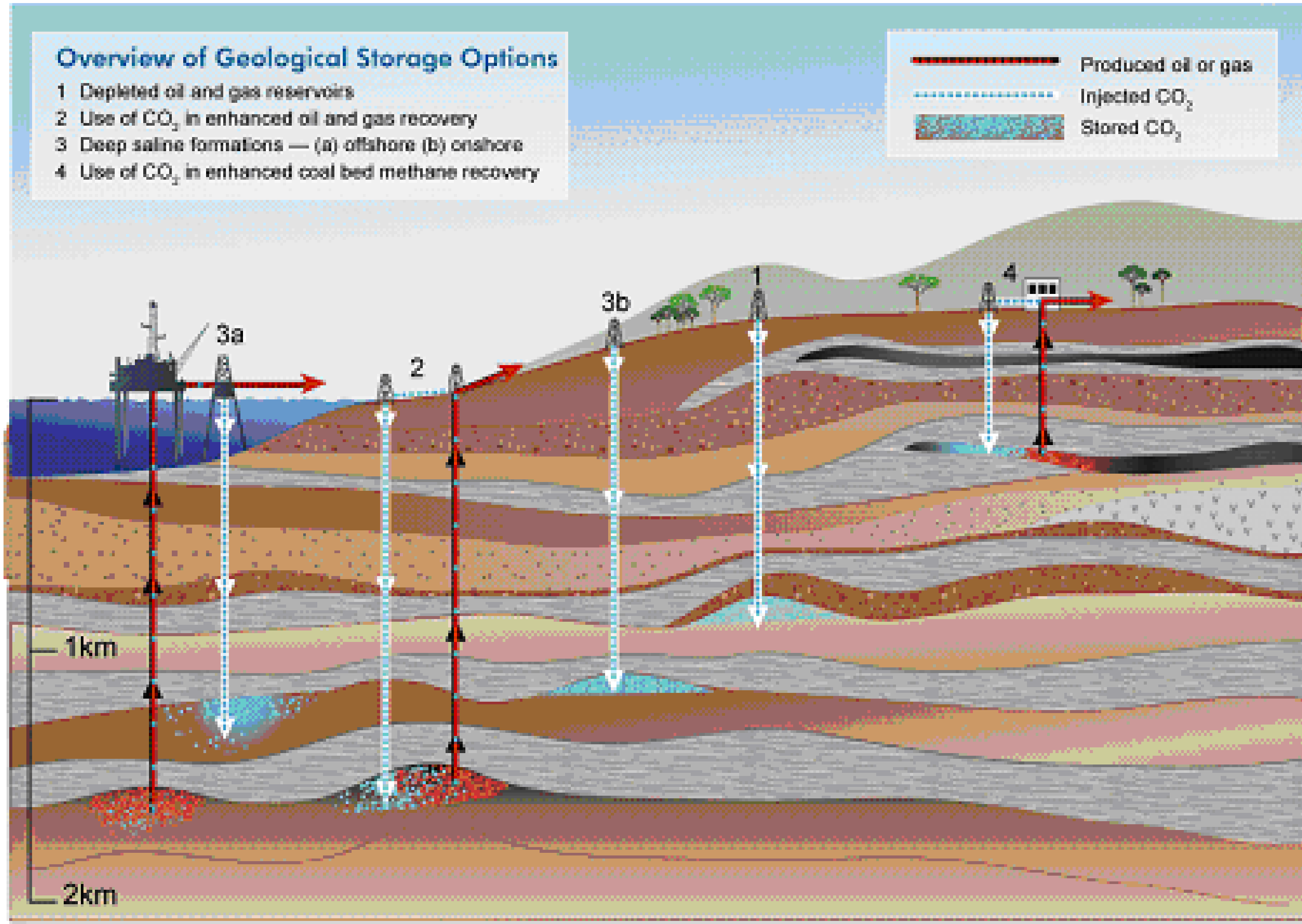
Criteria and Energy Requirements

- Large stationary point sources
- High CO_2 concentration in the waste, flue gas or by-product stream (purity)
- High pressure of CO_2 stream
- Close to suitable storage sites
- Energy
  - Additional energy use of 10 - 40% (for same output)
  - Capture efficiency: 85 - 95%
  - Net CO_2 reduction: 80 - 90%
  - Assuming safe storage



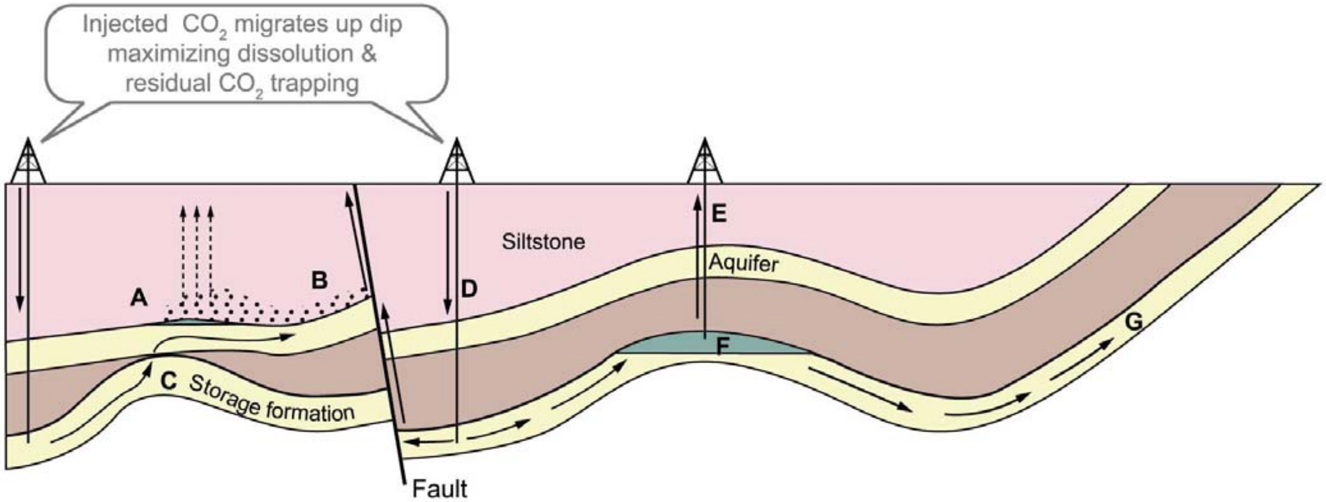
IPCC (2005) Special Report on CO2 Capture and Storage

Geologic Storage



IPCC (2005) Special Report on CO2 Capture and Storage

Potential Leakage Mechanisms and Remediation Strategies



Potential Escape Mechanisms

A. CO_2 gas pressure exceeds capillary pressure & passes through siltstone	**B.** Free CO_2 leaks from A into upper aquifer up fault	**C.** CO_2 escapes through 'gap' in cap rock into higher aquifer	**D.** Injected CO_2 migrates up dip, increases reservoir pressure & permeability of fault	**E.** CO_2 escapes via poorly plugged old abandoned well	**F.** Natural flow dissolves CO_2 at CO_2 / water interface & transports it out of closure	**G.** Dissolved CO_2 escapes to atmosphere or ocean

Remedial Measures

A. *Extract & purify ground-water*	***B.*** *Extract & purify ground-water*	***C.*** *Remove CO_2 & reinject elsewhere*	***D.*** *Lower injection rates or pressures*	***E.*** *Re-plug well with cement*	***F.*** *Intercept & reinject CO_2*	***G.*** *Intercept & reinject CO_2*

IPCC (2005) Special Report on CO2 Capture and Storage

Cost

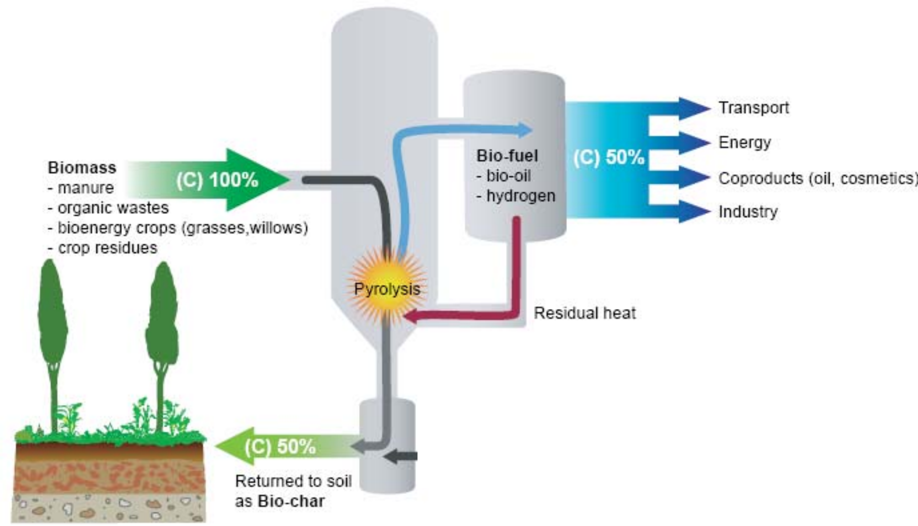
CCS component	Cost range
Capture: Power Plant	55 - 275 US$/tC net captured
Capture: Gas Processing or Ammonia Production	18 - 202 US$/tC net captured
Capture: Other Industrial Sources	92 - 422 US$/tC net captured
Transportation	3.7 – 29 US$/tC transported 250km
Storage: Geological	1.8 – 29 US$/tC injected
Storage: Ocean	18 - 110 US$/tC injected
Mineral Carbonation	183 - 367 US$/tC net mineralized

$0 $100 $200 $300 $400

IPCC (2005) Special Report on CO2 Capture and Storage

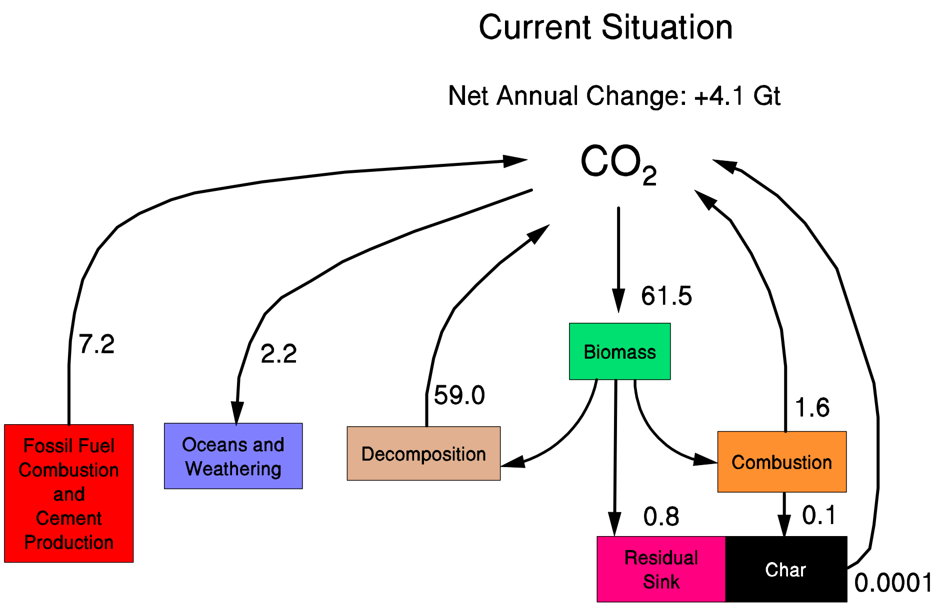
Terrestrial Storage

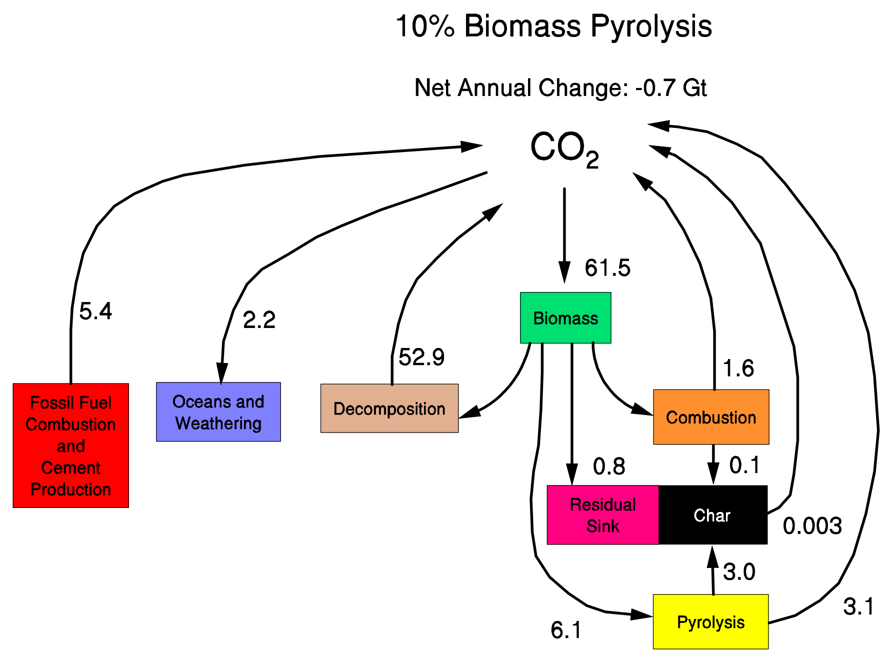
- Standing biomass (trees, crops)
  - Currently 466 Gt C
  - Near saturation
- Soil carbon
  - Currently 2011 Gt C
  - Near saturation
- Biochar
  - Potential storage capacity 380 Gt C in top 15 cm
  - Product of pyrolysis
  - C-negative energy



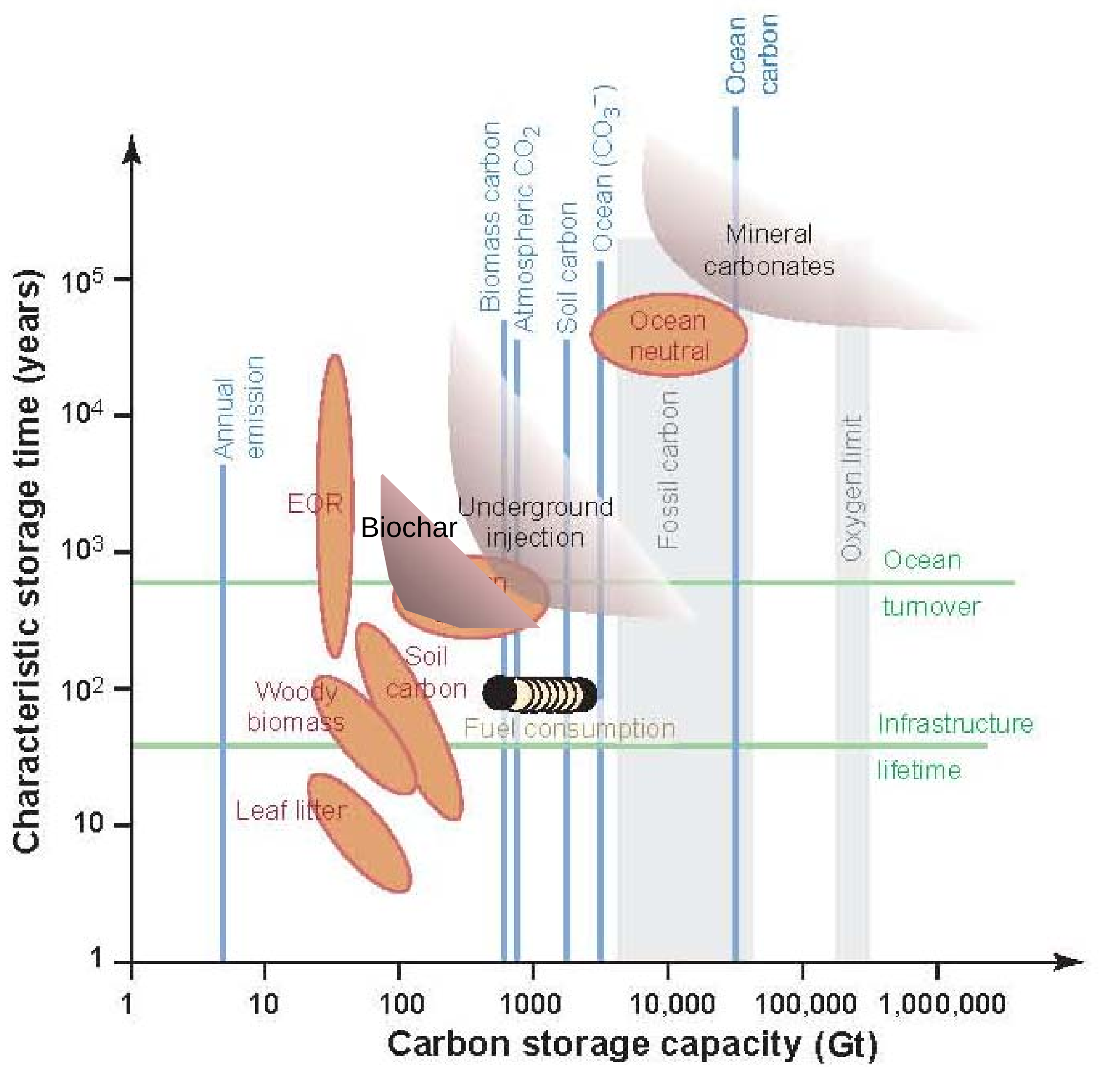
Courtesy of J. Lehmann (2007)

Preliminary Analysis of Biochar Potential





C Sequestration Capacities and Longevity



(Modified) Lackner et al., 2003, Science 300:1677

Biofuel Feedstocks and Conversion Options

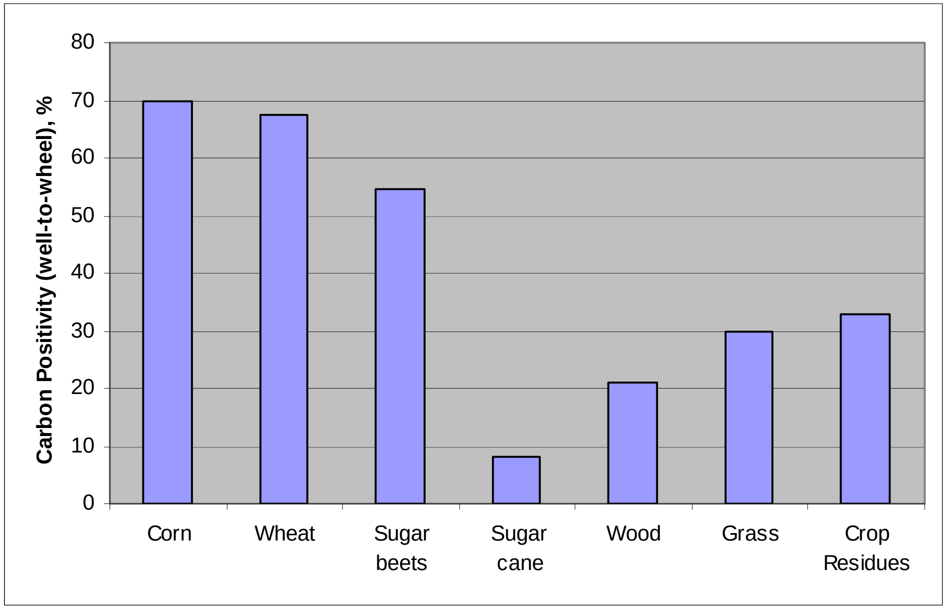
- Trees
  - 77% of plant biomass
  - Growth rate highest in tropics
  - Eucalyptus, poplar, pine, oak
- Grains
  - Corn, wheat, sweet sorghum
  - Oil seeds
- Crop Residues
  - Corn stover, wheat straw
- Grasses
  - Switchgrass, Miscanthus, Native prairie
  - Sugar cane
- Forages
  - Alfalfa
  - New thick-stemmed variety (USDA-ARS-PSRU St. Paul))

- Sugar/starch alcohol
- Cellulosic alcohol
- Combustion
  - Co-firing, biodiesel
- Pyrolysis
  - Bio-oil, bio-gas, biochar

	Trees	Grains	Crop Residues	Grasses	Forages
Sugar/Starch Alcohol					
Cellulosic Alcohol					
Combustion					
Pyrolysis					

Ethanol

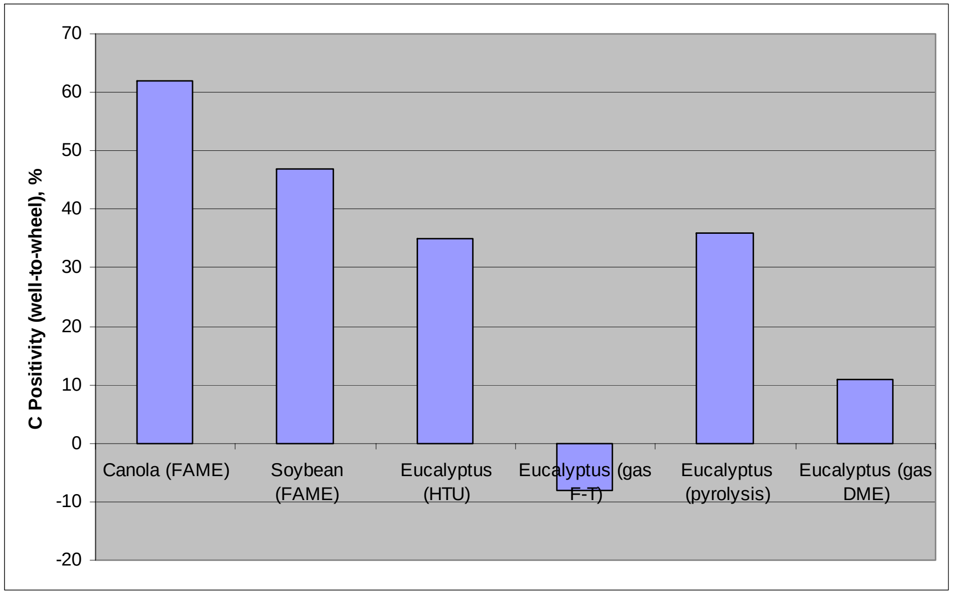
- Well-to-wheel analysis shows GHG reductions by all options
- Cellulosic is an improvement over corn/wheat starch
- Sugar cane clearly least C-positive
- Pyrolysis of residues for biochar could enhance C-negativity



Data modified from IEA (2004) Biofuels for transport.

Diesel

- Predictive assessment by Netherlands Energy Agency (1999)
- FAME diesel competitive with ethanol
- Gasification and cellulosic processes have best potential (Fischer-Tropsch is C-negative!)
- Pyrolysis (biochar probably assumed to be combusted in process)
- Additional assessments by same group yielded C-negative values for cellulosic ethanol



Data modified from IEA (2004) Biofuels for transport.

Combustion and Pyrolysis

- Combustion ca. 97-99% efficient
- Slagging issues from high silica and potassium make co-firing at <10% biomass most effective approach
- At best, biomass combustion is C-neutral or slightly C-positive

- Several pyrolysis approaches available with comparable energy output
- Pyrolysis is C-negative when more than 30-34% char is produced
- Carbon-negativity is assured when pyrolysis/combustion combined with sequestration

Pyrolysis Method	Energy Efficiency	Char	Liquid	Volatile	Carbon Positivity
	------------------------------ % -----------------------------				
Slow	30	40-50	<10	40-50	-33 to -66
Fast	34	10-50	30-50	10-30	70 to -47
Hydrothermal	34	100	0	0	-194

The N_2O Problem

- Recent work (Crutzen et al., 2007, Atmos.Chem. Phys. Disc. 7:11191) suggests that globally, N_2O production averages at 4% (+/- 1%) of N that is fixed
- IPCC reports have accounted only for field measurements of N_2O emitted, which show values close to 1%, but ignore other indicators discussed by Crutzen et al.
- If 4% is correct, then combustion of biofuels except for high cellulose (low-N) fuels will actually increase global warming relative to petroleum due to large GWP of N_2O

Trade-offs

	N_2O	Food	Water	Soil Quality	Maturity	Cost	Robust
EtOH-Starch							
EtOH-Sugar cane							
EtOH-Cellulose							
Combustion	varies	varies		varies			
Pyrolysis	varies	char	char	char			

Possible Evolution of Technologies

- Cellulose-based technologies will increase at expense of starch due to competition for food, concerns about soil quality, and higher N_2O emissions
- Pyrolysis has strongest C-negativity and as technology matures will be primary approach for mitigating climate change
- Pyrolysis and combustion are robust, flexible as to their feedstocks, and relatively inexpensive technologies—if liquid fuel suitable for transportation can be developed from these technologies at reasonable cost, cellulosic ethanol will have small niche market

Acknowledgments

Research supported in part by the U. S. Department of Energy's (DOE) National Energy Technology Laboratory and in part by the DOE's Office of Biological and Environmental Research (OBER) through the Carbon Sequestration in Terrestrial Ecosystems (CSiTE) project. Research was performed at the W.R. Wiley Environmental Molecular Sciences Laboratory, a national scientific user facility at the Pacific Northwest National Laboratory (PNNL) sponsored by the DOE-OBER. The PNNL is operated for the DOE by Battelle Memorial Institute under contract DE AC06 76RL01830.