GLOBAL CLIMATE AND ENERGY PROJECT | STANFORD UNIVERSITY

Negative Emissions 101

Chris Field and Jennifer Milne

GCEP Symposium 2013 – http://gcep.stanford.edu/symposium
Stanford University
October 8-9, 2013

Background

- Rapidly increasing emissions
- Appreciation of the long life of atmospheric CO_2
- Climate change & disaster risk
- Ocean acidification
- Negative emissions technologies

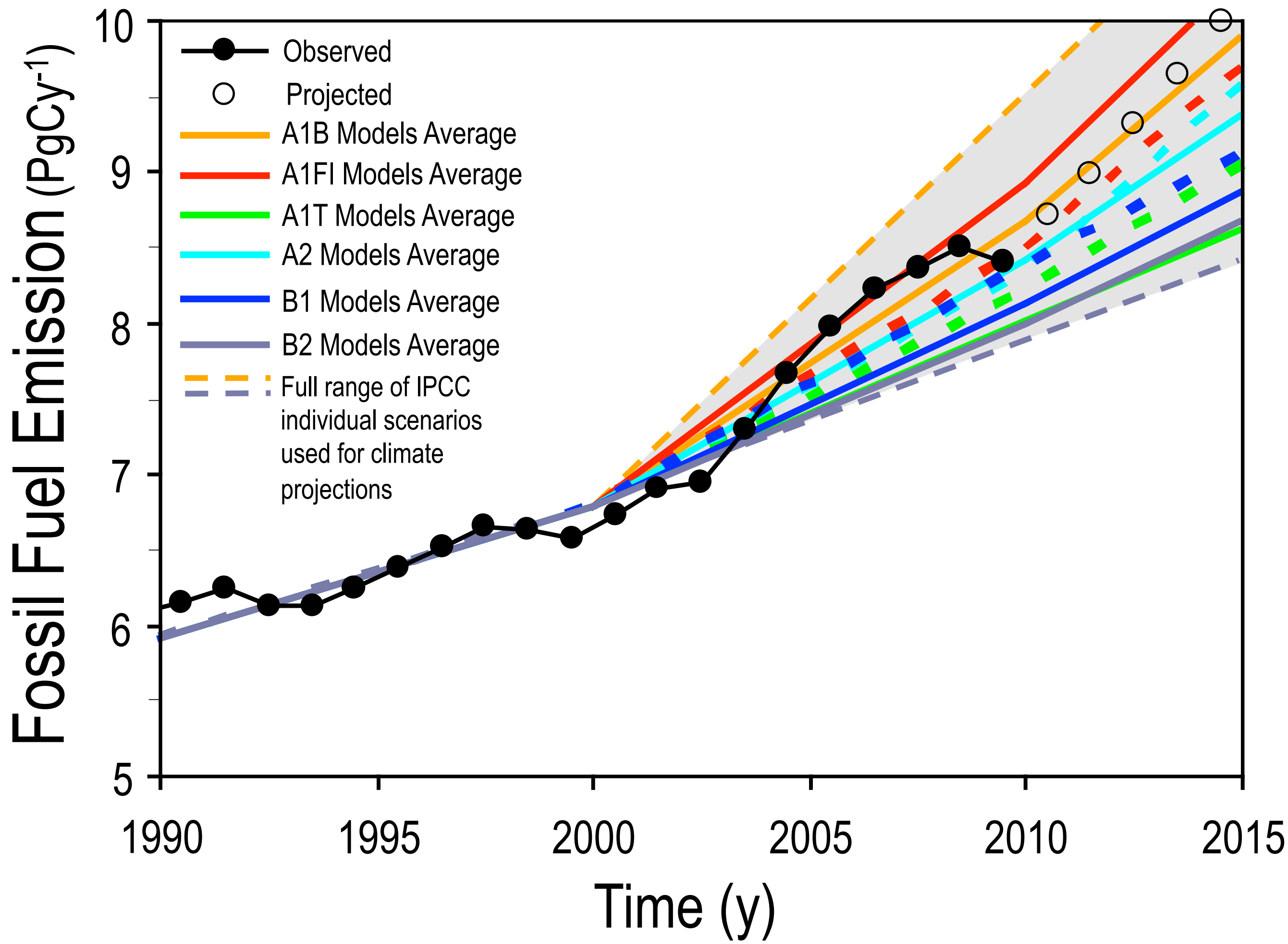
Some Conversions

1 ppm by volume of atmosphere CO_2 = 2.13 Gt C

1Gt C = 3.664 Gt CO_2

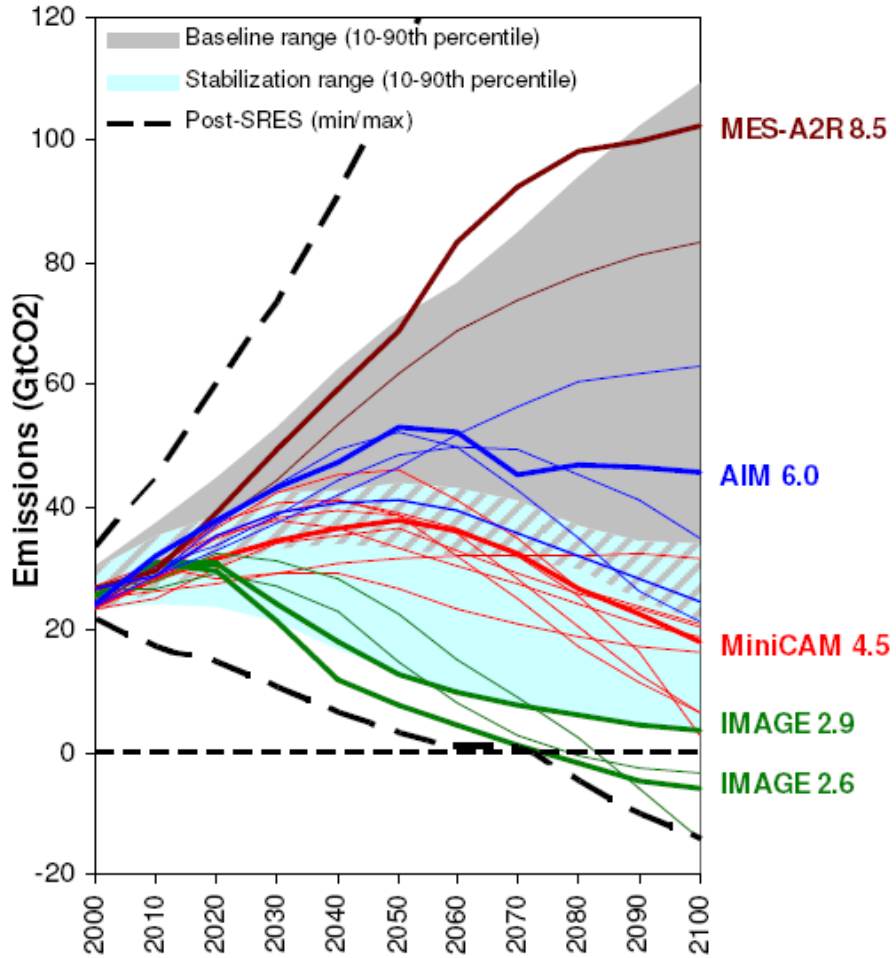
giga	G	10^9
peta	P	10^{15}

Fossil Fuel Emissions: Actual vs. IPCC Scenarios



Updated from Raupach *et al*. 2007, *PNAS*; Data: Gregg Marland, Thomas Boden-CDIAC 2010; International Monetary Fund 2010

Representative Concentration Pathways (RCPs)

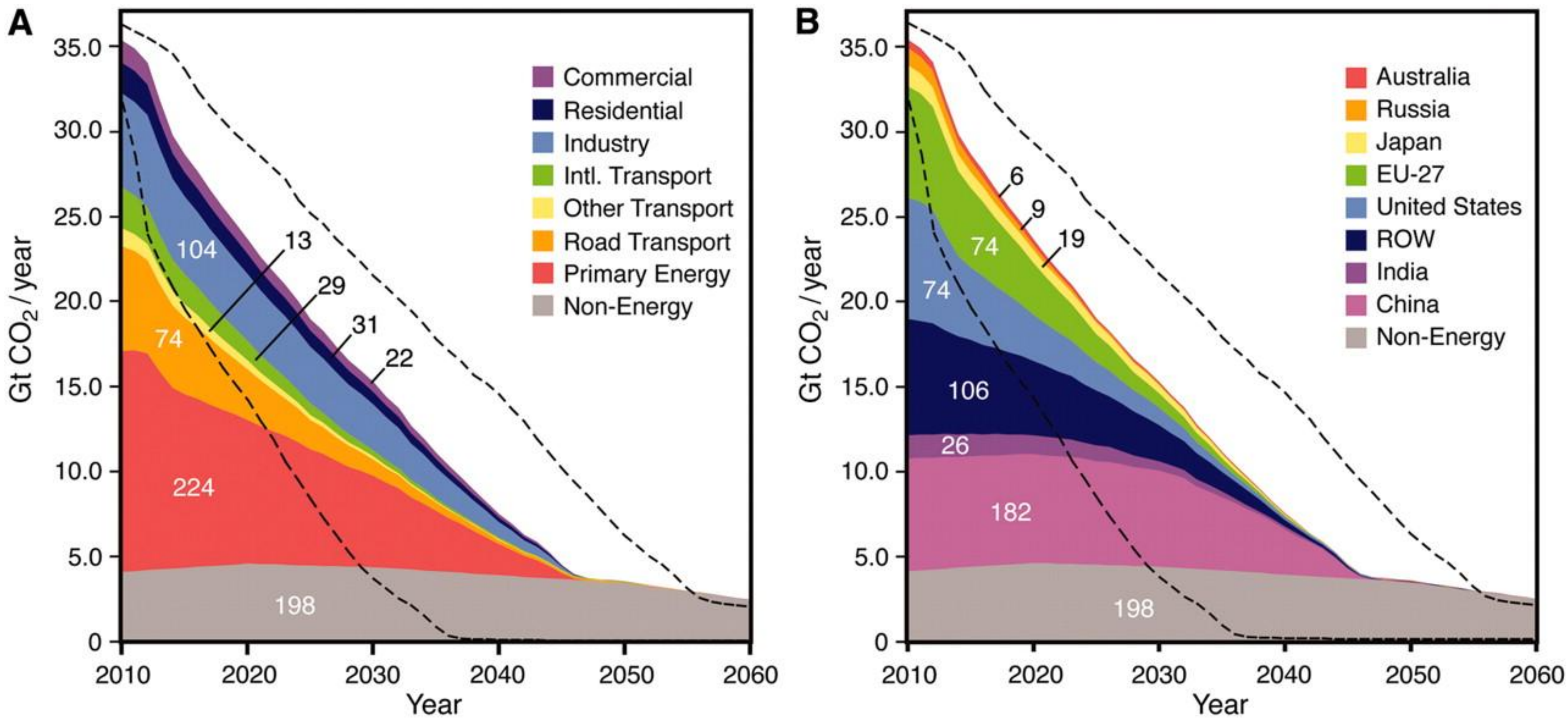


Moss, R., *et al.*, 2010

Anthropogenic Contribution

- Sources – energy sector major contributor
- Effects – ocean acidification, insulation – temp rise
- Potential consequences – various

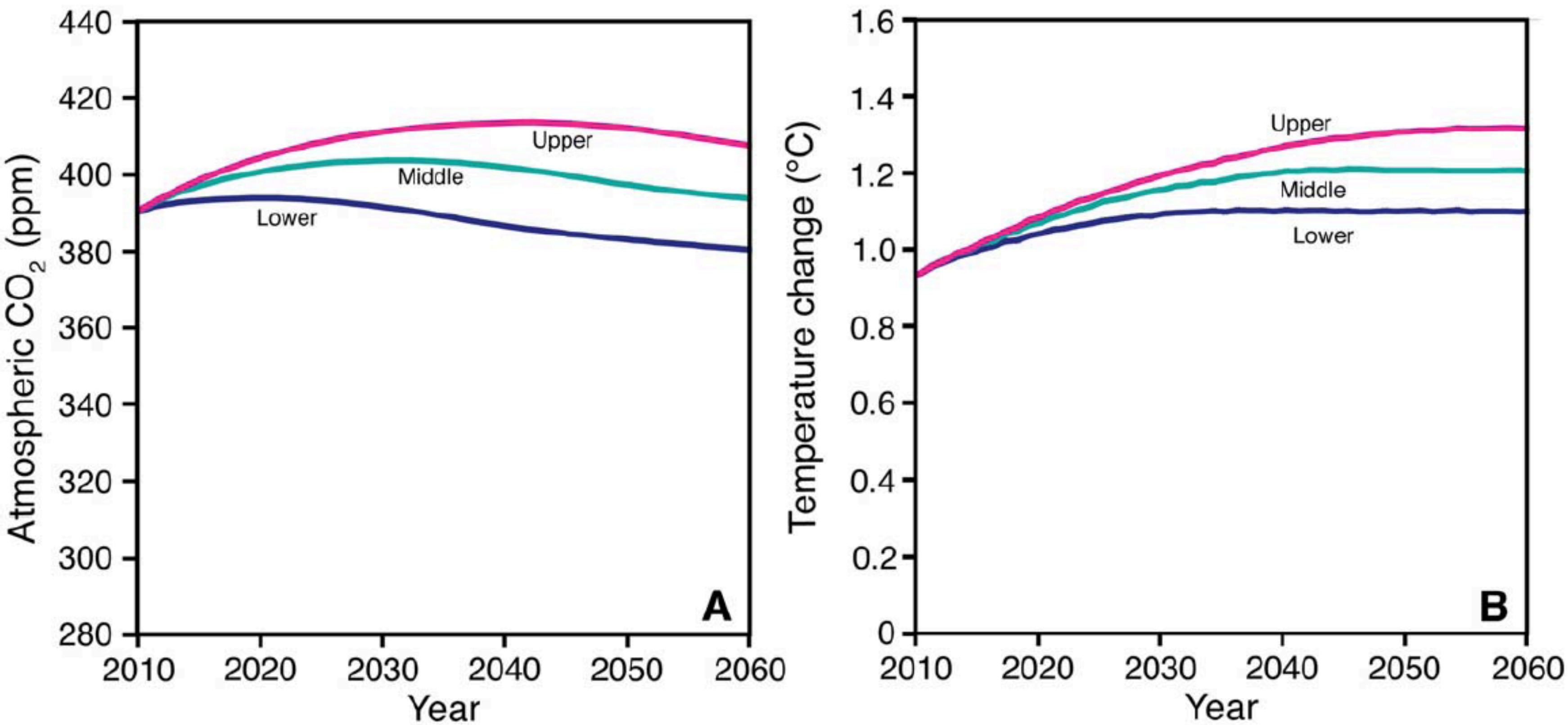
Future CO_2 Emissions from Existing Energy Infrastructure



- Committed emissions

Davis *et al*. *Science*, 2010

Committed Emissions from Energy and Transportation Infrastructure

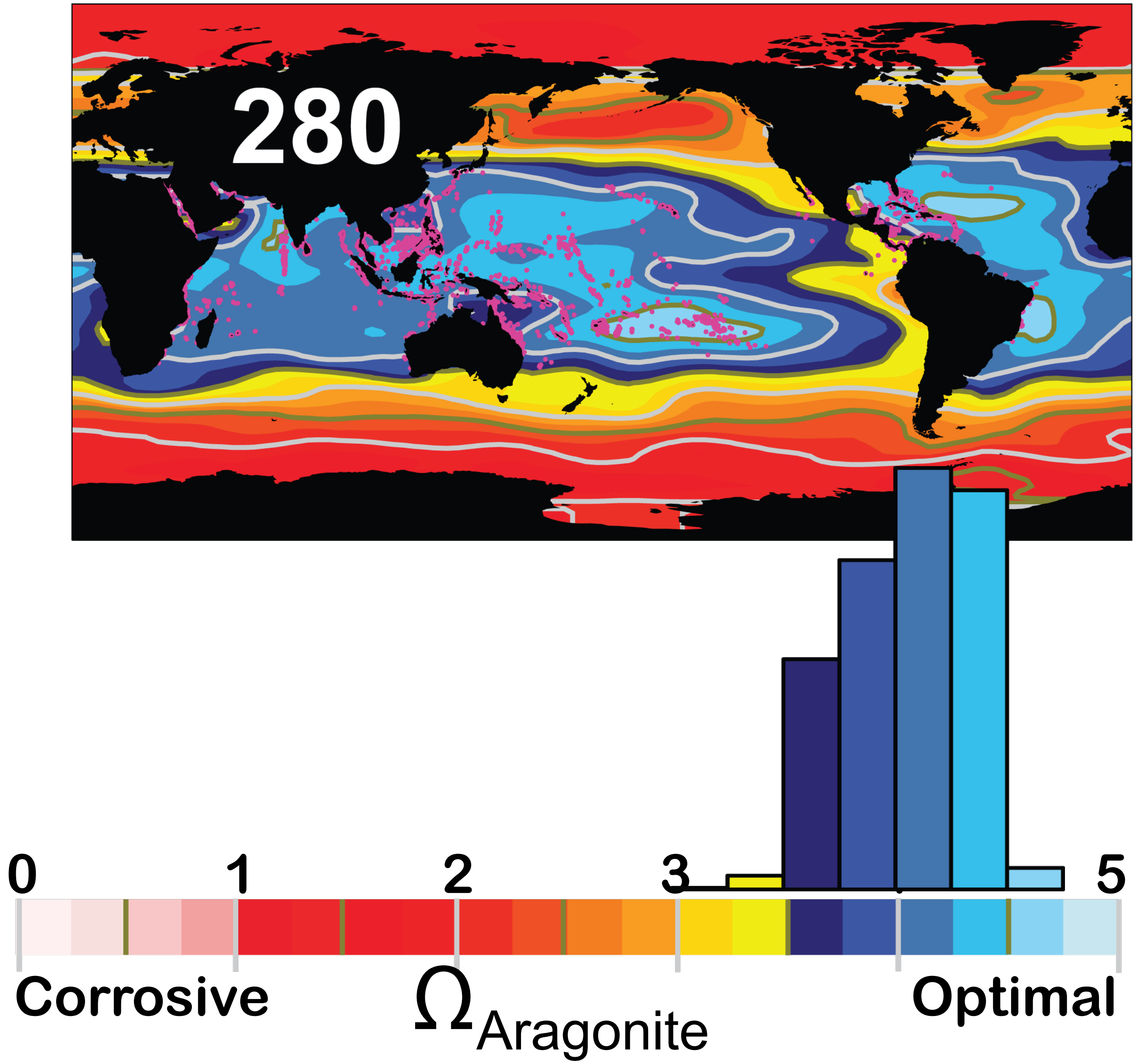


Davis *et al*. *Science*, 2010

Carbon dioxide level

Coral reef distribution

Chemical conditions helping drive reef formation



Cao and Caldeira, 2008

Carbon dioxide level

Coral reef distribution

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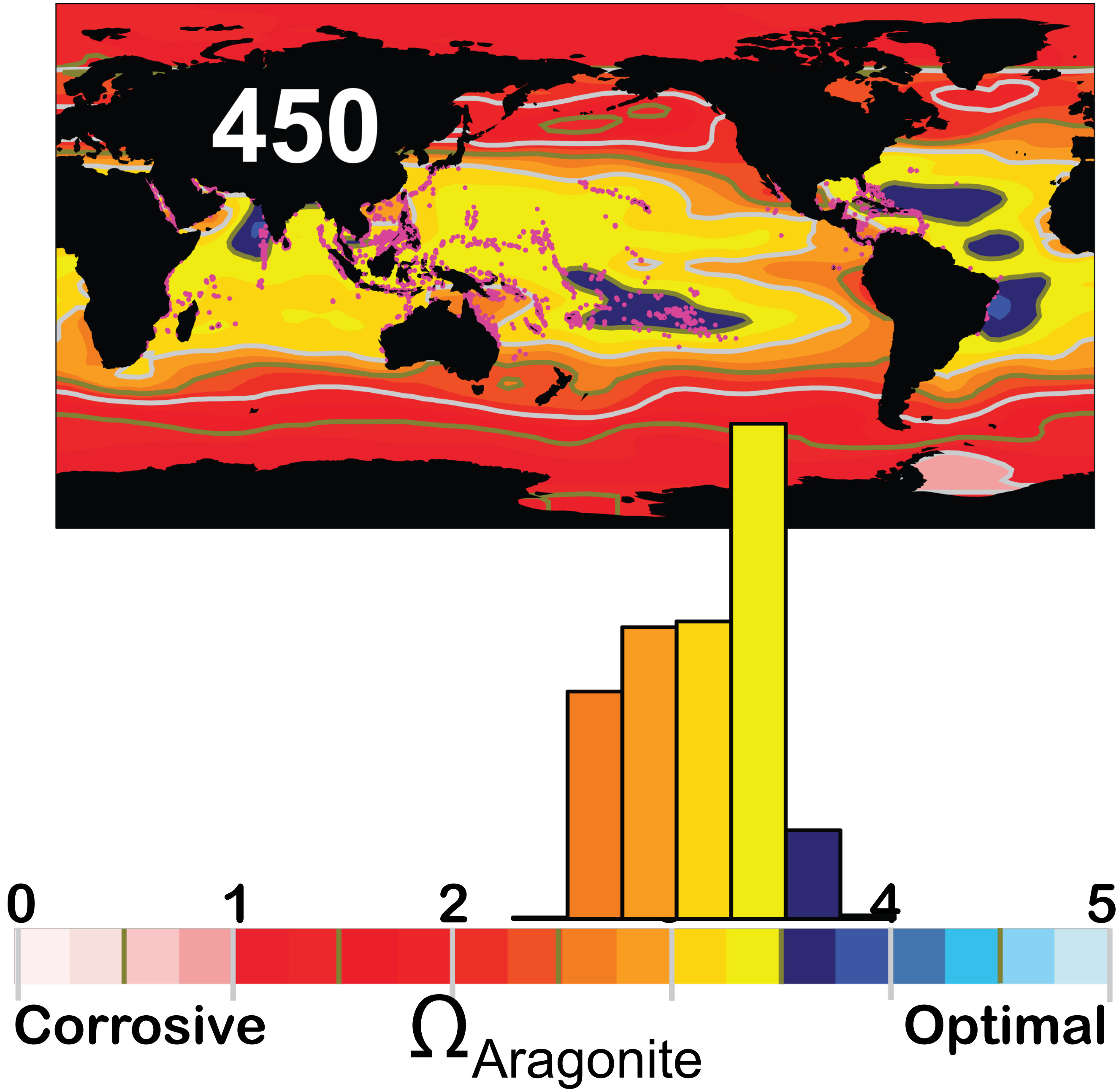
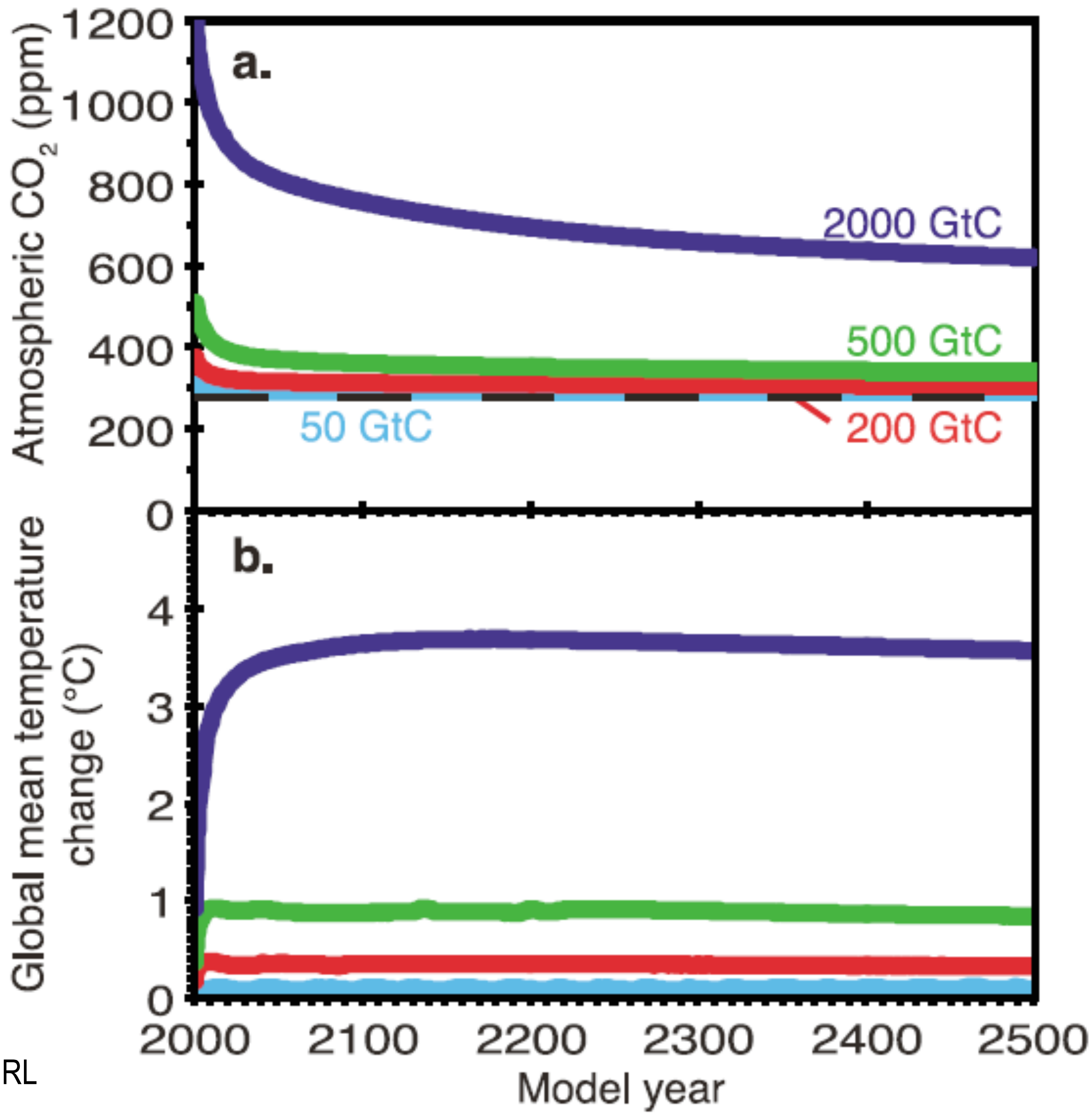


Cao and Caldeira, 2008

Permanent Climate Change



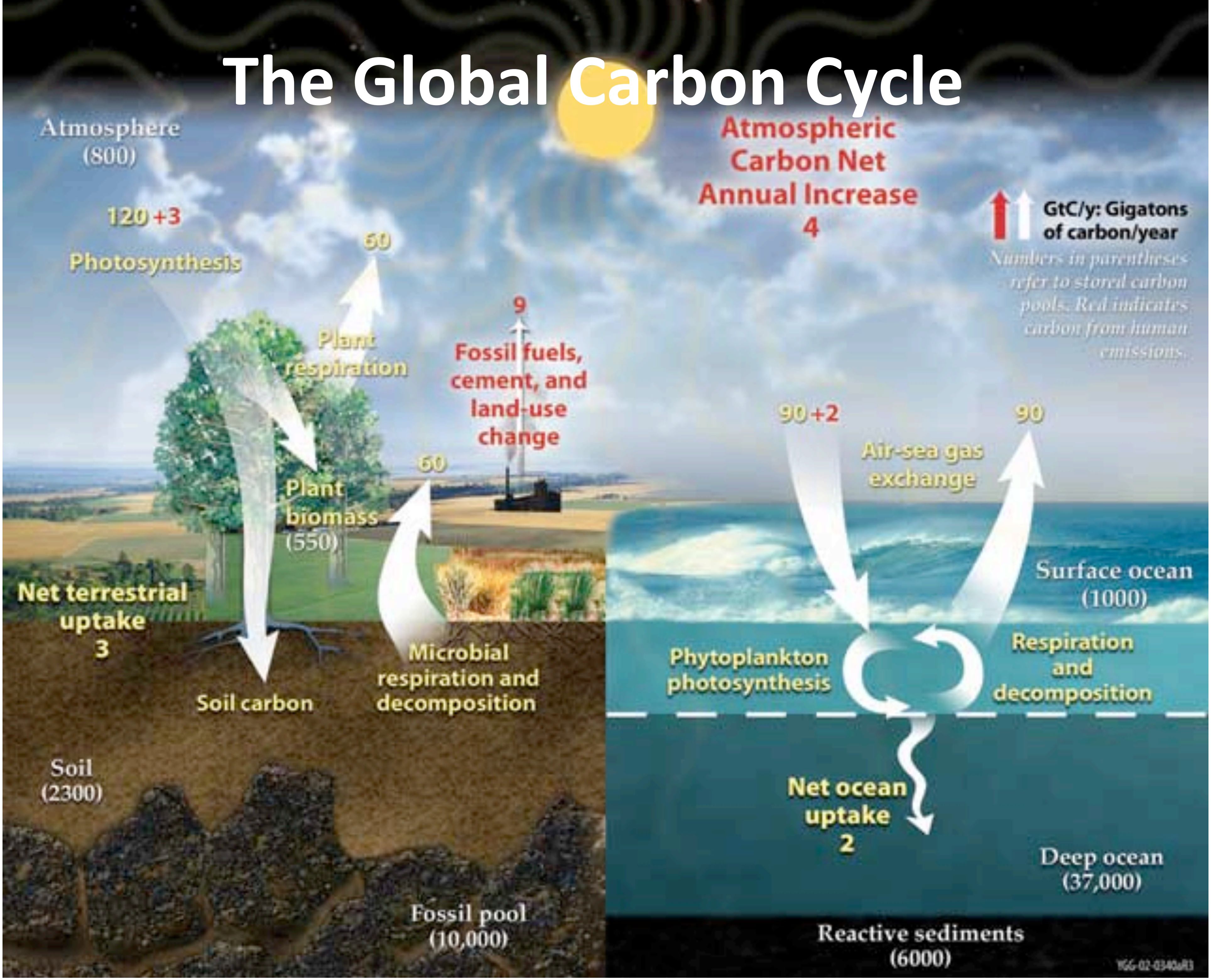
Matthews and Caldeira 2007 GRL

How Much CO_2 do we Need to Capture and Store?

Potential Carbon Sinks

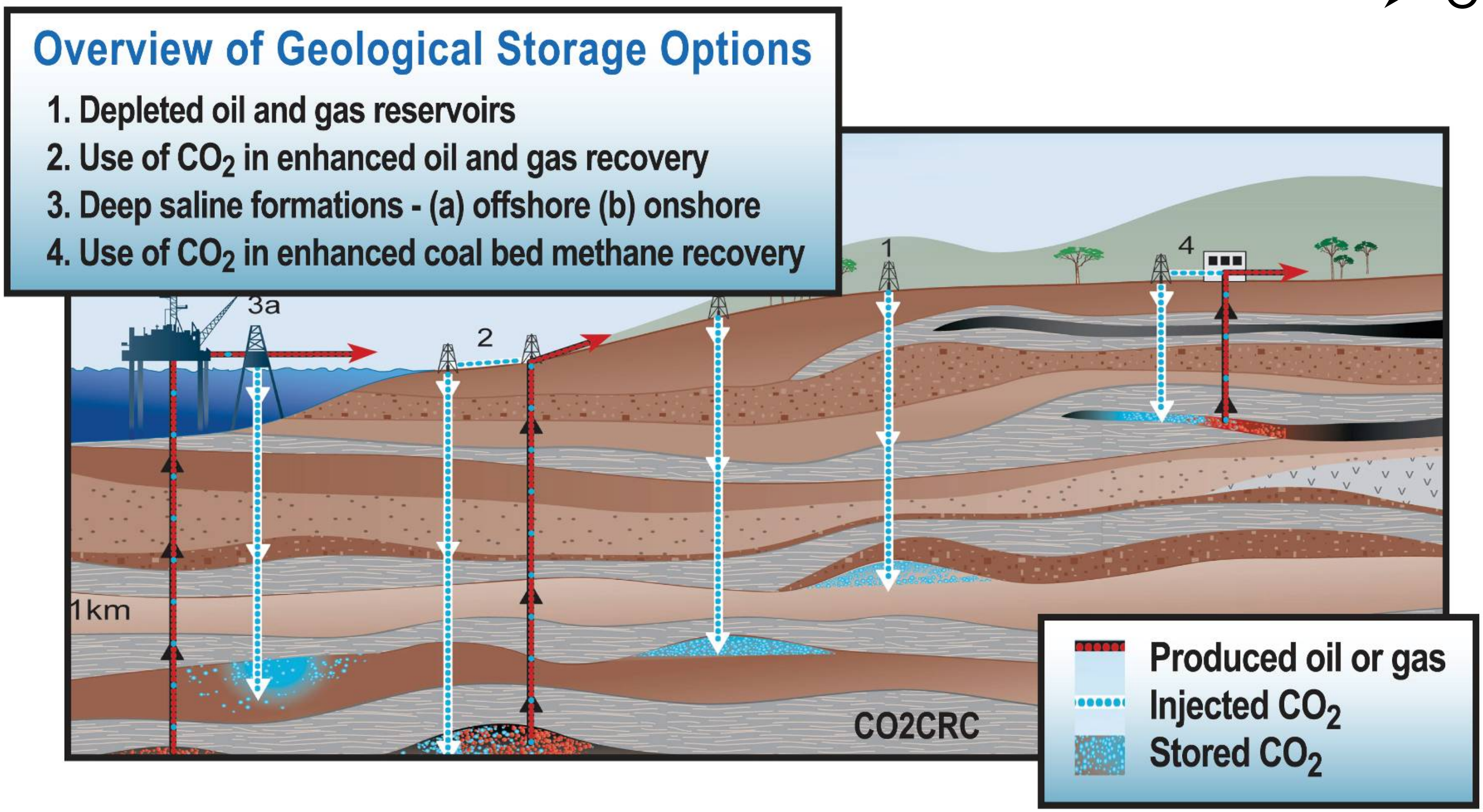
- Terrestrial biomass – biochar, soils, trees, grasses etc – storage time?
- Marine biomass – storage time?
- Geologic sequestration
- Ocean sequestration
- Other – reuse, materials

The Global Carbon Cycle



CO_2 Sequestration Options

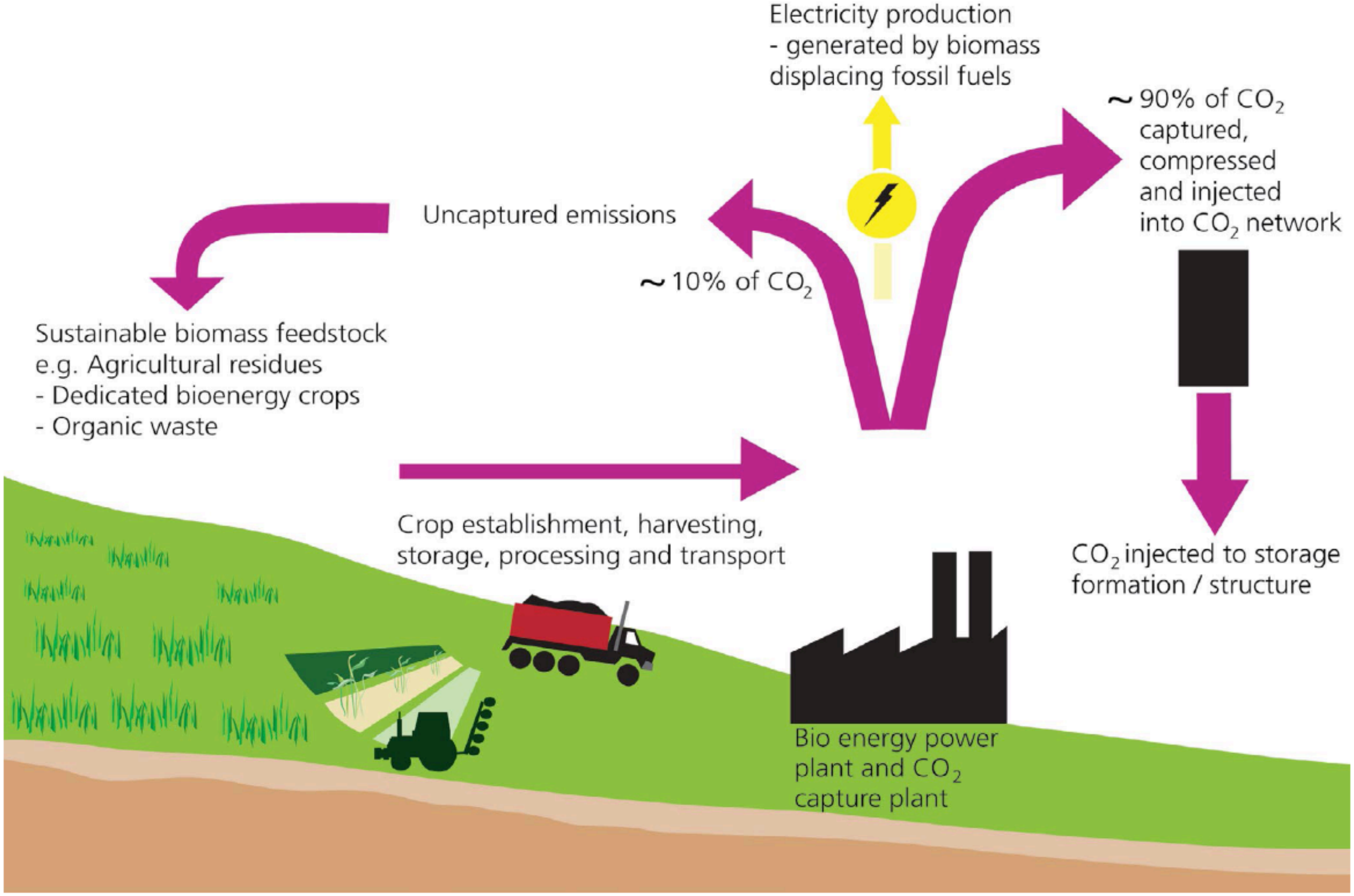
- Deep geological formations
  - Oil and gas
  - Coal
  - Saline aquifers
  - Basalts
  - Deep ocean sediments
- Solids
  - Minerals
  - Cement
  - Other



Bioenergy with Carbon Capture and Storage (BECCS)

Scalability depends on:

- Global biomass potential
- Logistical considerations for large scale biomass supply chains
- Carbon sequestration availability



See Grantham Institute for Climate Change Briefing paper No 8, Imperial College London, McGlashan *et al*., October 2012.

BECCS Projects

Source: Biorecro, Global CCS Institute ,2011

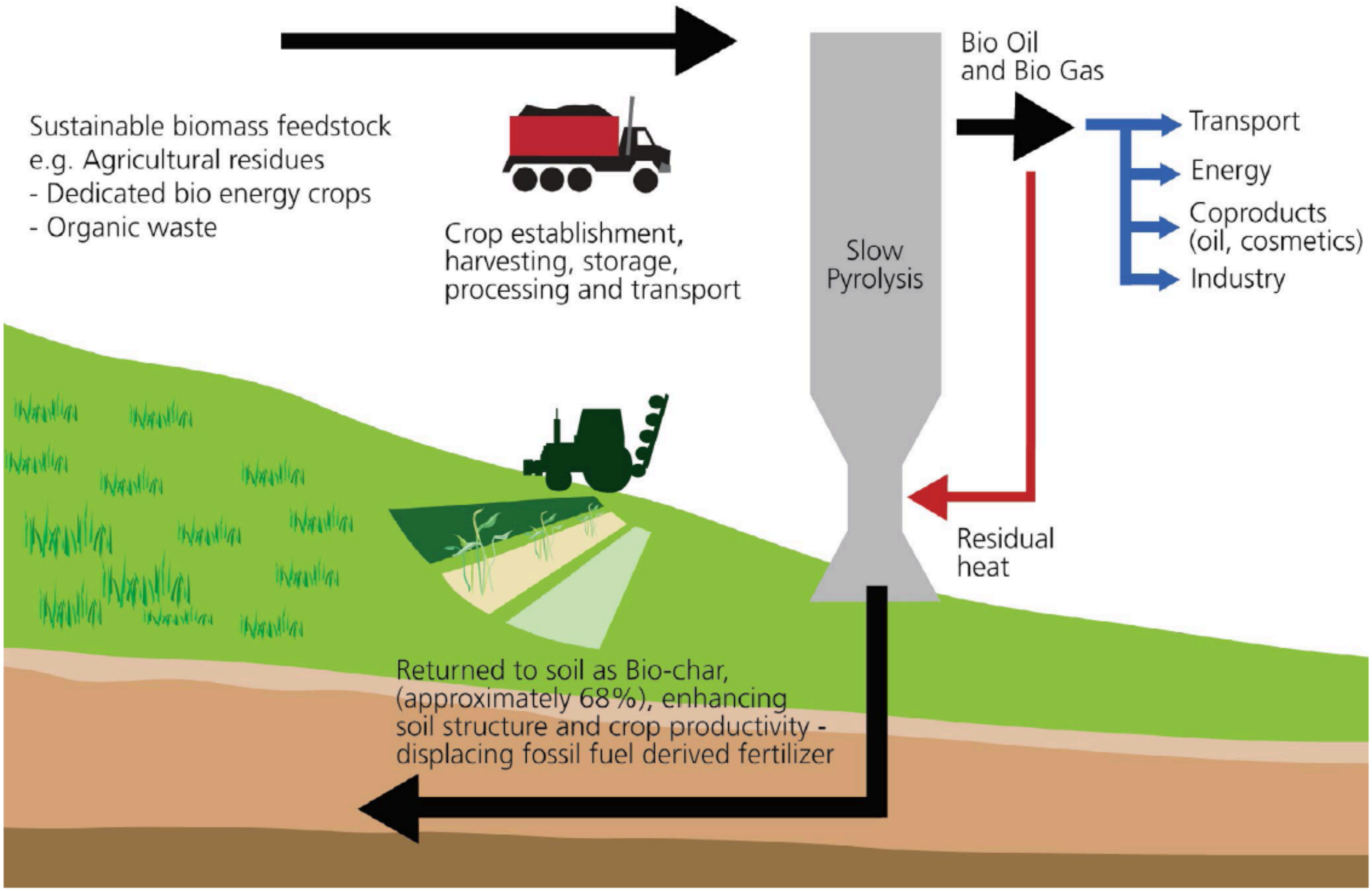
CAPTURE FACILITY

- Pulp and Paper
- Ethanol
- Gasification and others

STORAGE TYPE

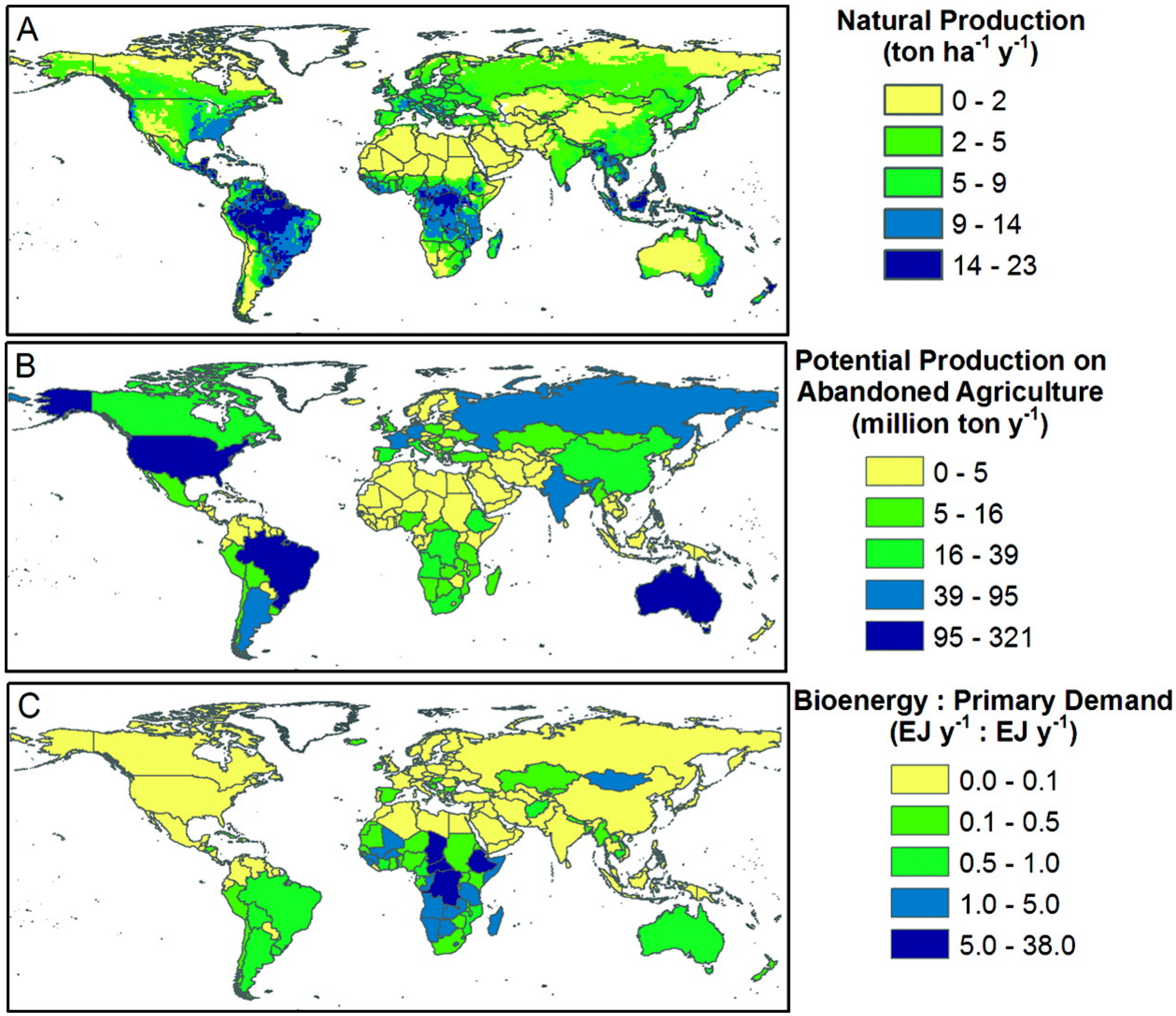
- △ Geological
- ○ Beneficial reuse
- □ Geological and/or beneficial reuse

Biochar



See Grantham Institute for Climate Change Briefing paper No 8, Imperial College London, McGlashan *et al*., October 2012.

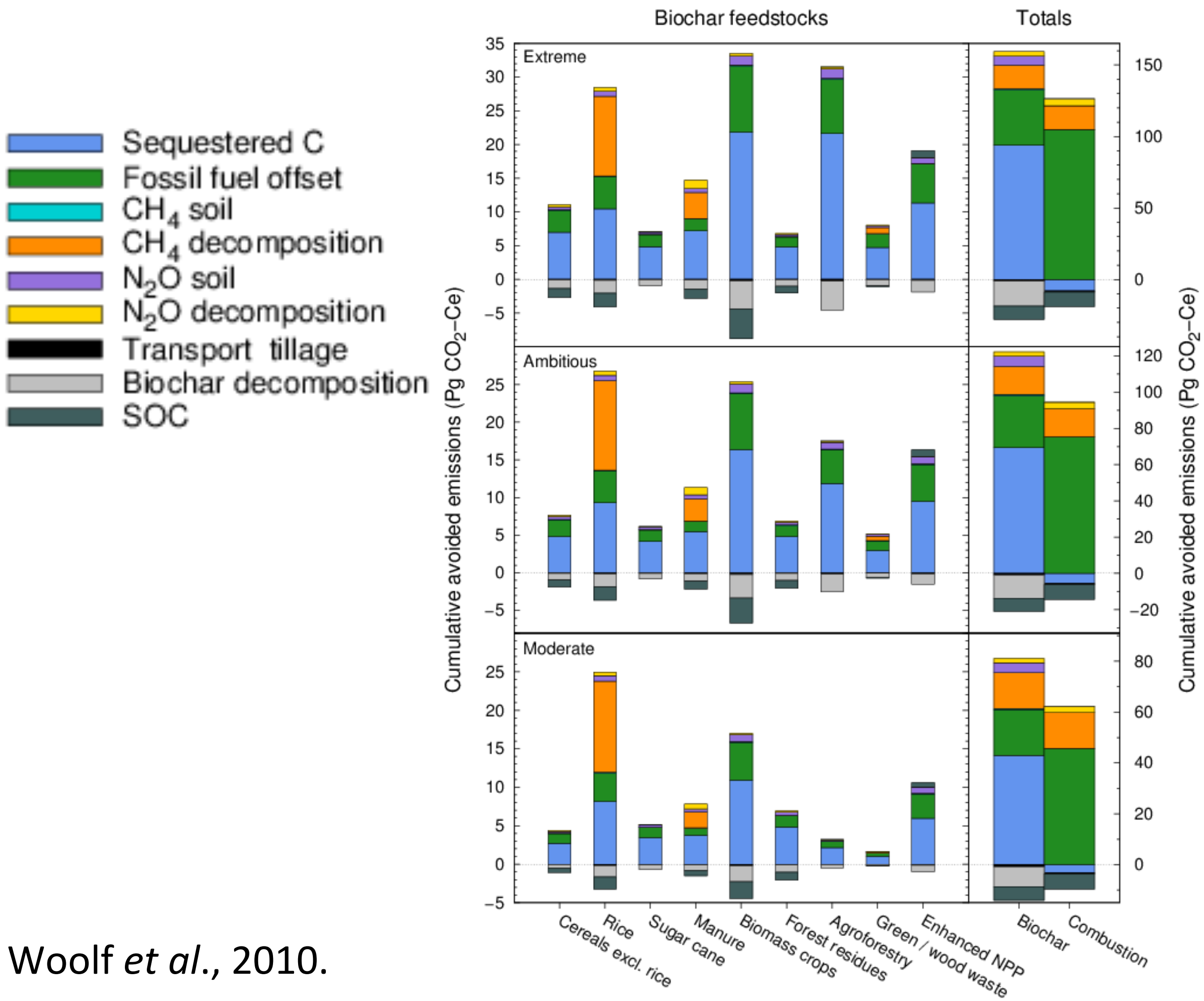
Estimates of NPP



Campbell *et al*., *Env. Sci. Technol*. (2008) 42,5791

The energy content of biomass is assumed to be 20 kJ g−1

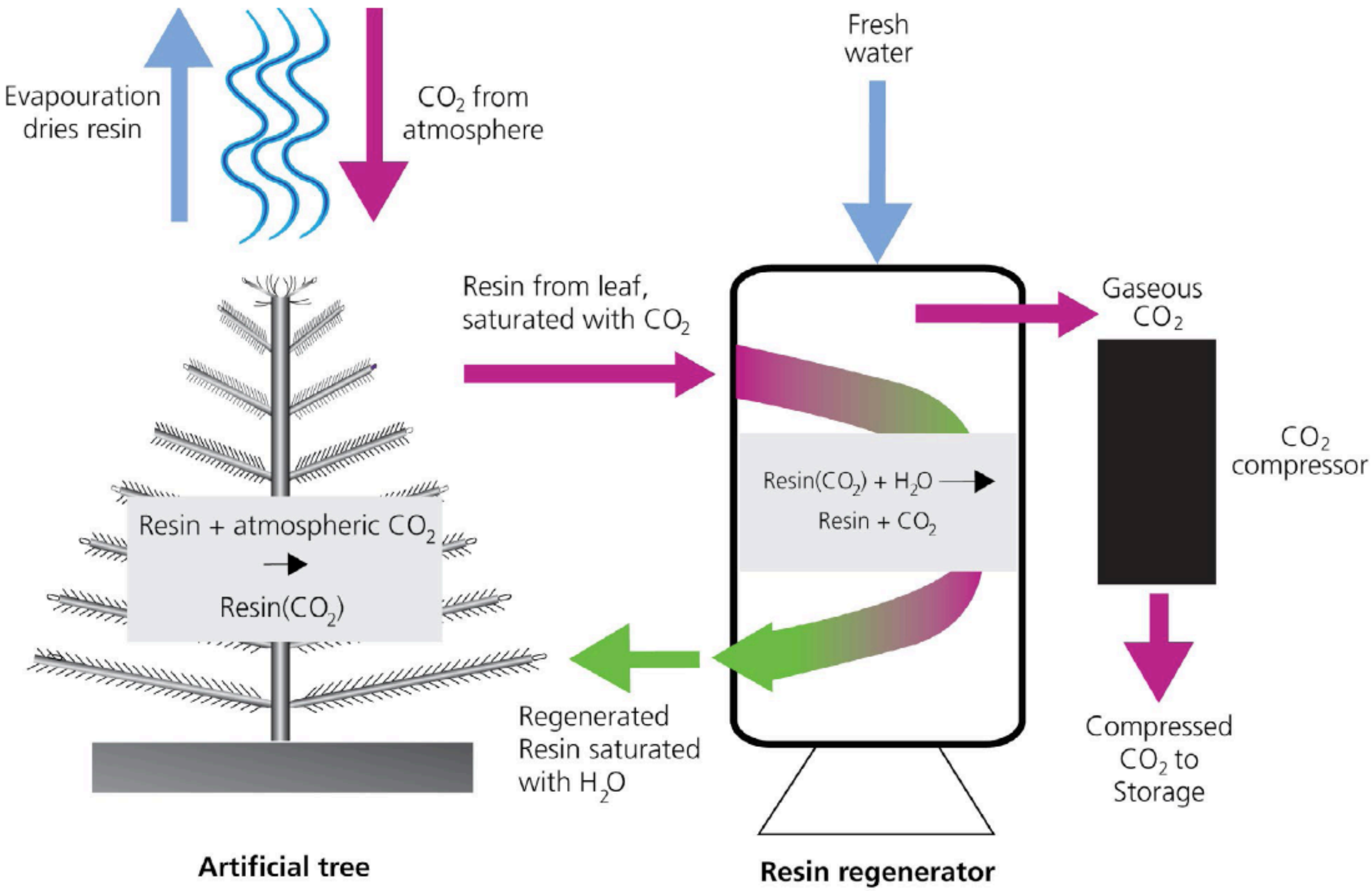
Predicted Avoided Emissions Through Biochar Feedstocks



Maximum Sustainable Technical Potential

See Woolf *et al.*, 2010.

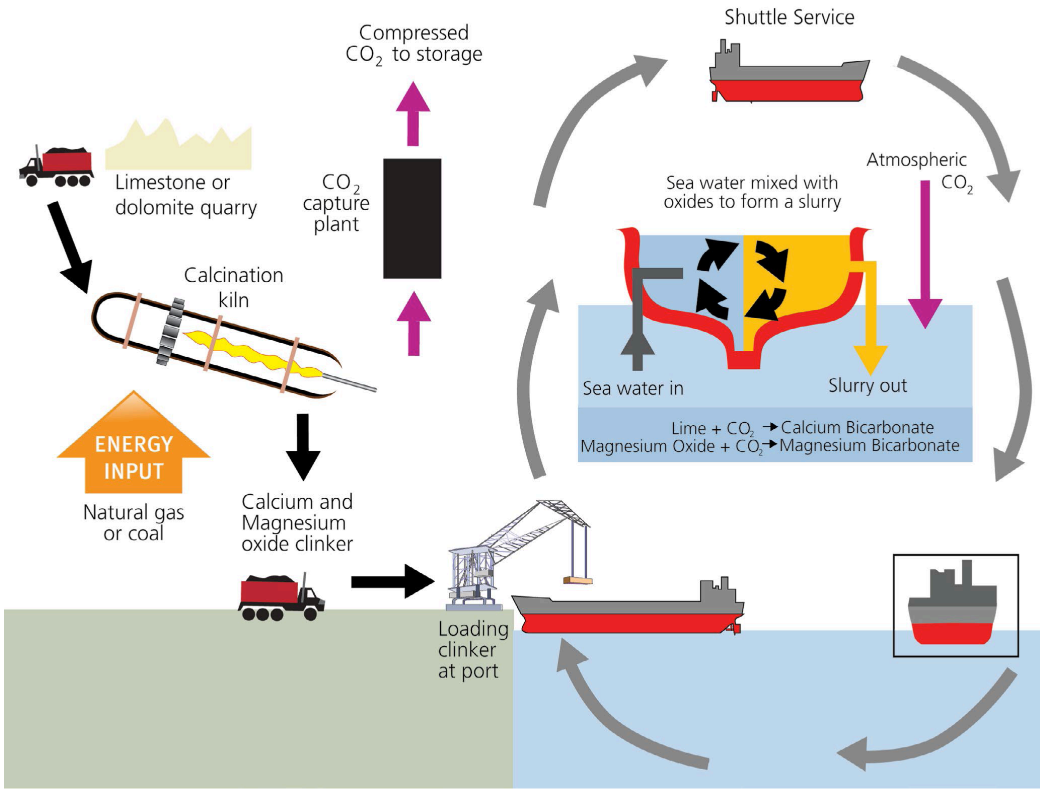
Artificial Trees or DAC



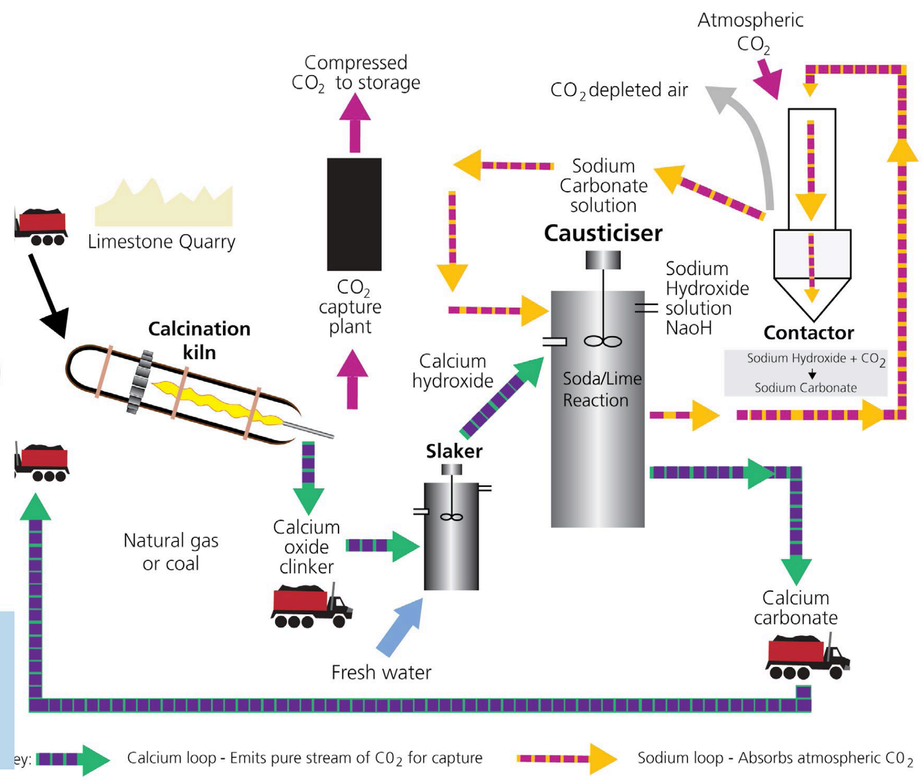
See Grantham Institute for Climate Change Briefing paper No 8, Imperial College London, McGlashan *et al*., October 2012.

Other Routes to Negative Emissions

Ocean Disposal



Lime-Soda Process



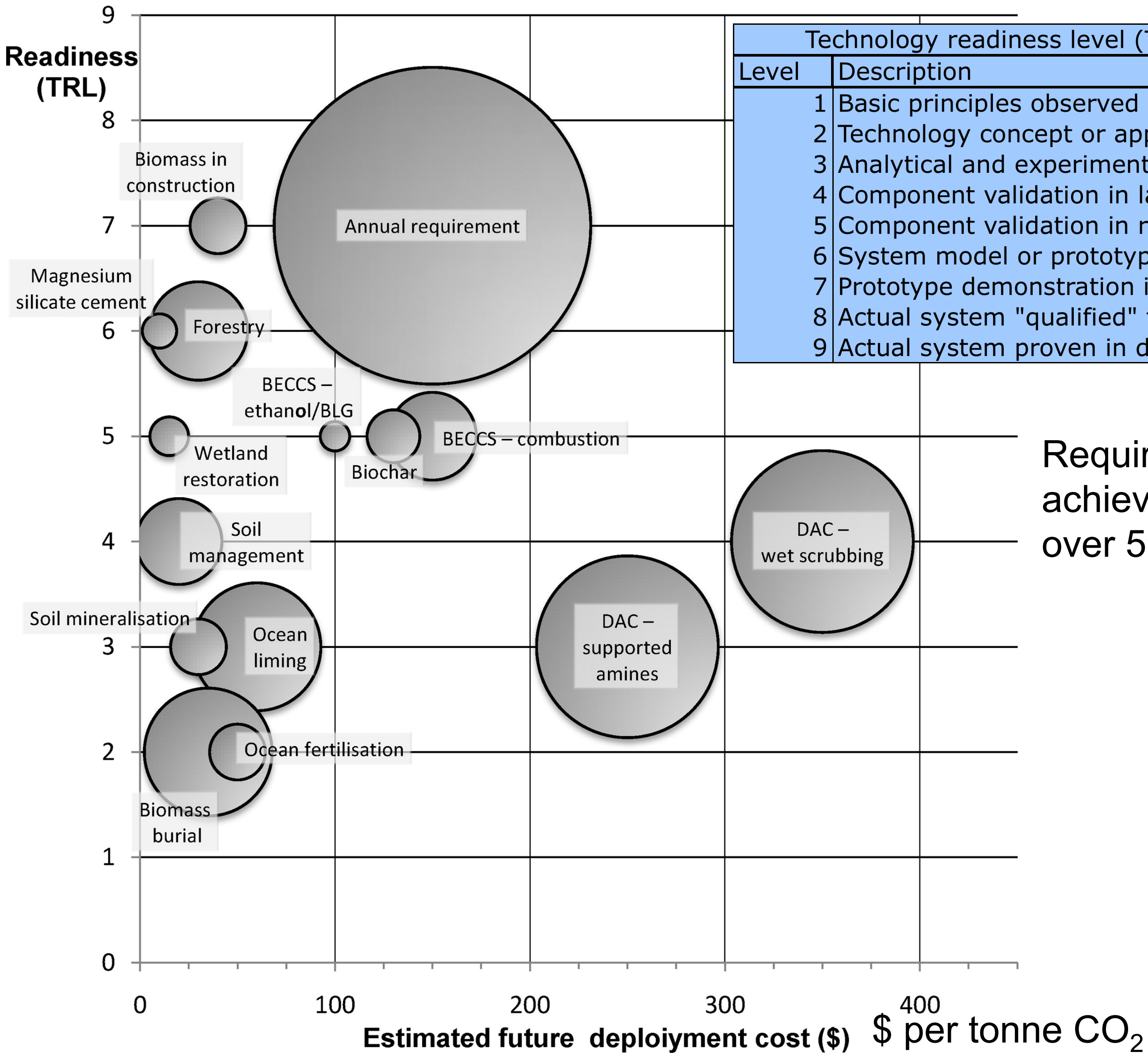
See Grantham Institute for Climate Change Briefing paper No 8, Imperial College London, McGlashan *et al*., October 2012.

Energy, Raw Materials and Capital Costs for Technologies for Removal of 0.1ppm per year

	Item	Energy Heat (GWe)	Energy Work (GW)	Material	Equipment	Total Costs
Artificial Trees				Water	Trees	
	0.1 ppm	28.2	N/A	NK[#]	0.21 M	
	$/tCO_2e$	22.1	N/A	NK[#]	72.4	~95 $/tCO_2e$
Soda Lime				Limestone	Absorption Units	
	0.1 ppm	39.6	148.6	minimal	200 units	
	$/tCO_2e$	31.1	24	minimal	99	~155 $/tCO_2e$
Augmented Ocean Disposal				Limestone/ Dolomite	Lime Kilns / Bulk Carriers	
	0.1 ppm	9.4	123	0.76 Mt	1 unit / 1 ship	
	$/tCO_2e$	7.38	19.9	minimal	61.6 / 2.2	~90 $/tCO_2e$
Biochar				Biomass*	Pyrolysis 200 t/day	
	0.1 ppm	360.2	–	2.6 Bt	37000 units	
	$/tCO_2e$	–282.8	–	301.4	115.5	~135 $/tCO_2e$
BECCS				Biomass*	1GW Plant	
	0.1 ppm	102.2	–	0.64 Bt	~125 units	
	$/tCO_2e$	–80.2	–	86.9	52.1 – 104.2	~59 – 111 $/tCO_2e$

See Grantham Institute for Climate Change Briefing paper No 8, Imperial College London, McGlashan *et al*., October 2012.

Estimates of Capacity, Readiness and Cost of NETs

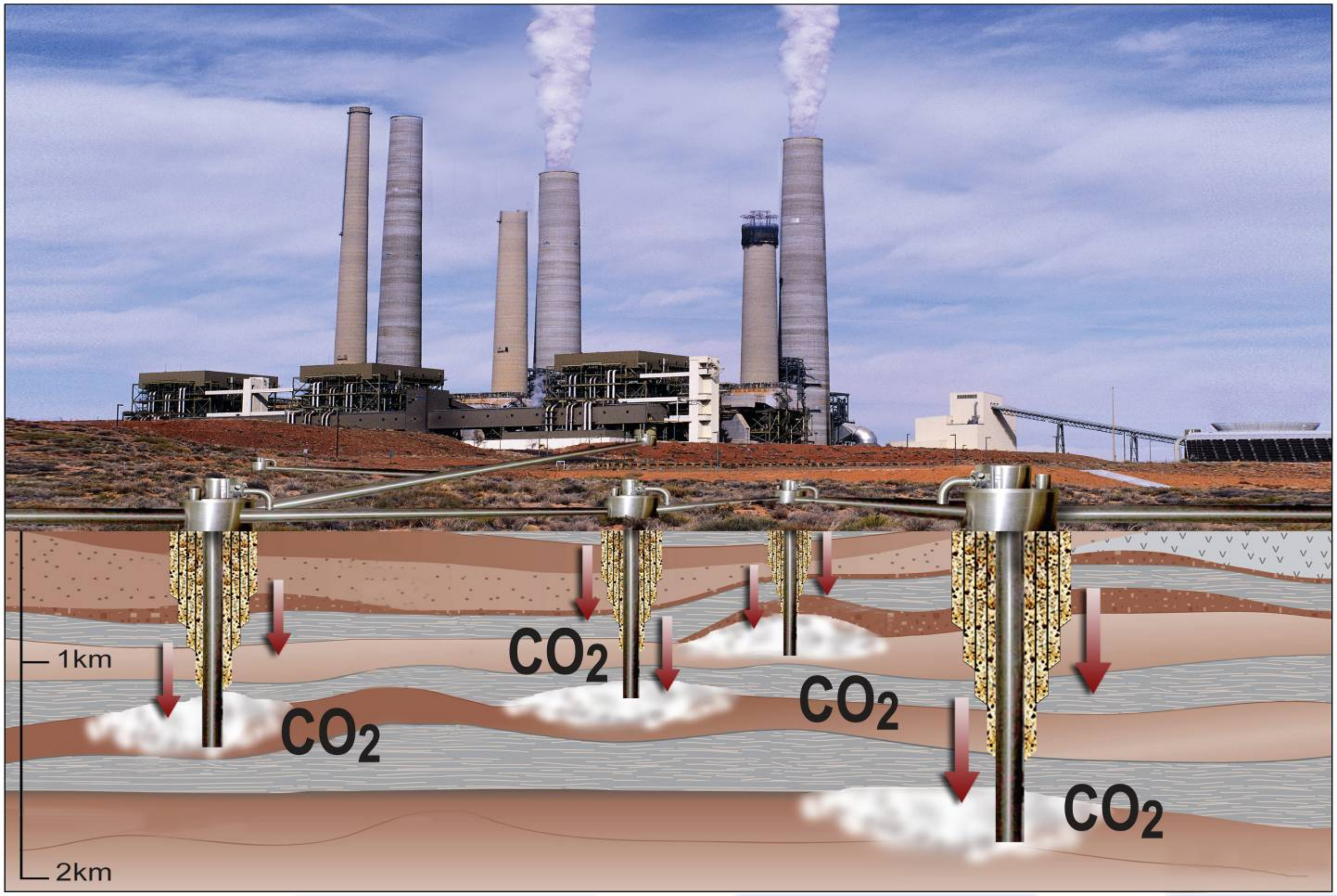


Technology readiness level (TRL) descriptions.	
Level	Description
1	Basic principles observed and reported
2	Technology concept or application formulated
3	Analytical and experimental critical function demonstrated
4	Component validation in laboratory environment
5	Component validation in relevant environment
6	System model or prototype demonstration in relevant environment
7	Prototype demonstration in operational environment
8	Actual system "qualified" through test and demonstration
9	Actual system proven in deployment

Required scale: 1200 Gt CO2 to achieve 350 ppm = (24Gt CO2 pa over 50 years).

From McLaren, *Process Safety and Environmental Protection*, 2012

Carbon Dioxide Capture and Sequestration Involves 4 Steps



Capture → Compression → Pipeline Transport → Geological Sequestration

Comparative Evaluation of CCS with Biomass and Fossil Fuels

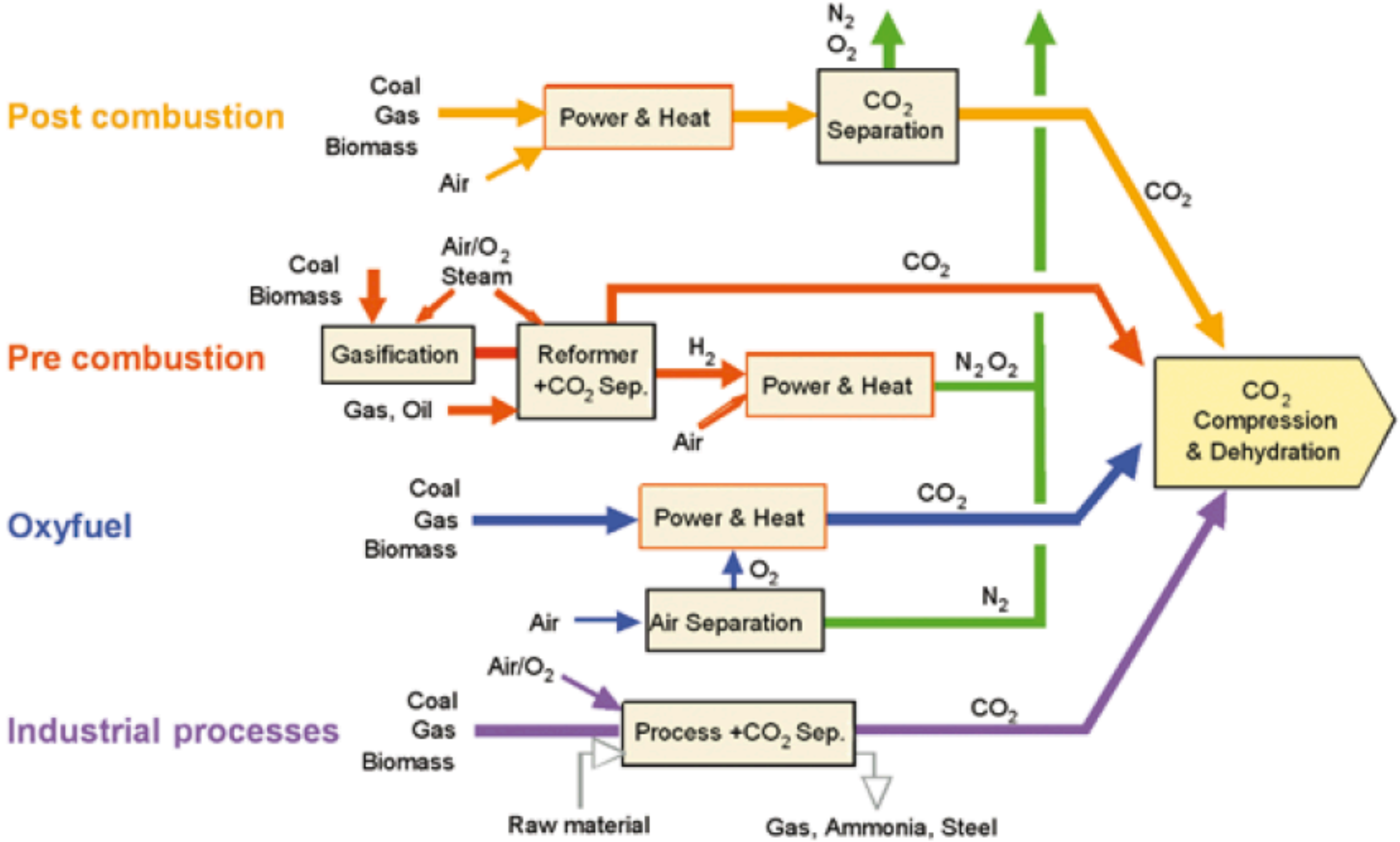
Fossil Fuels (inc. co-firing)

- Large central power generating stations or industry
  - 100 to 1000 MW
  - (1-10 MT CO_2/year)
- Efficient and reliable fuel delivery systems
- Consistent fuel source
- Year-round 24/7 operations

Biomass Feedstocks

- Potentially smaller scale power generation
  - 50 MW(1/10 size of fossil plants)
  - < 1 MT CO_2/year
- Significant scale-up and logistical issues with biomass delivery/storage
- Variable fuel sources
- Potentially variable operations depending on biomass feedstock availability

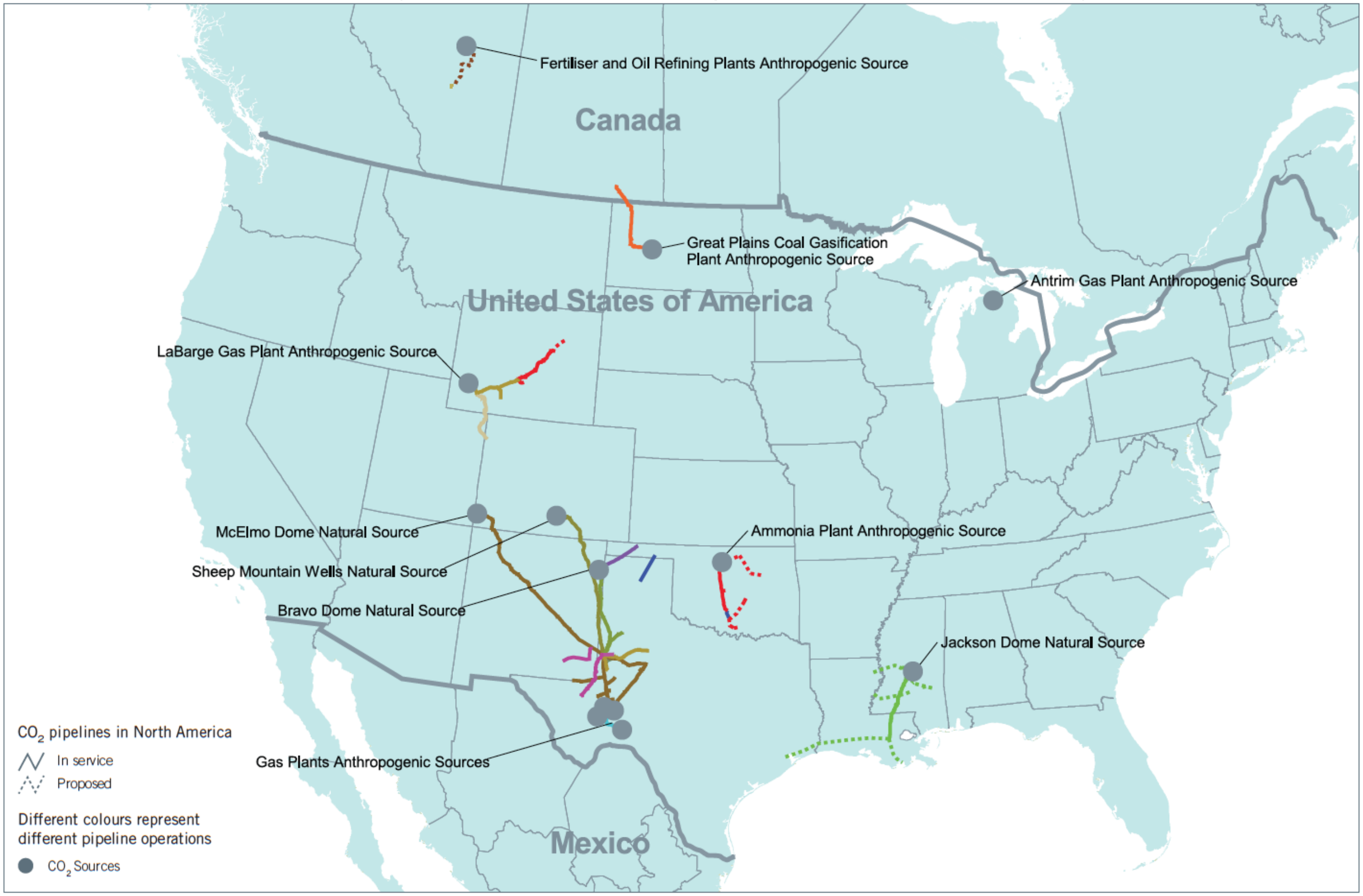
All conversions require compression and dehydration of CO_2



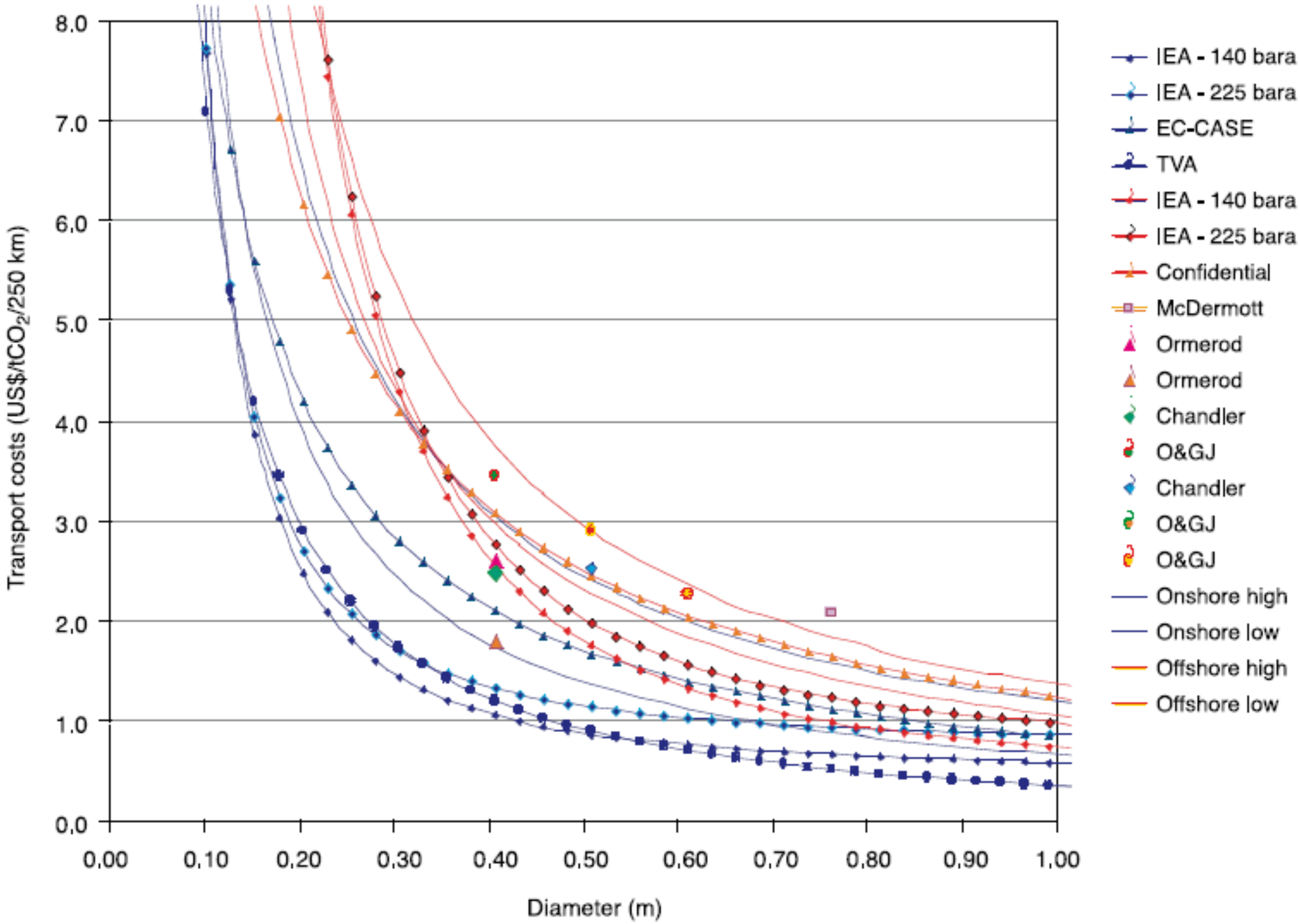
IPCC, 2005. Special Report on Carbon Dioxide Capture and Storage.

U.S. Existing and Planned CO_2 Pipeline Network

Currently transporting about 50 MT/year



Transport Cost Per Tonne of CO_2

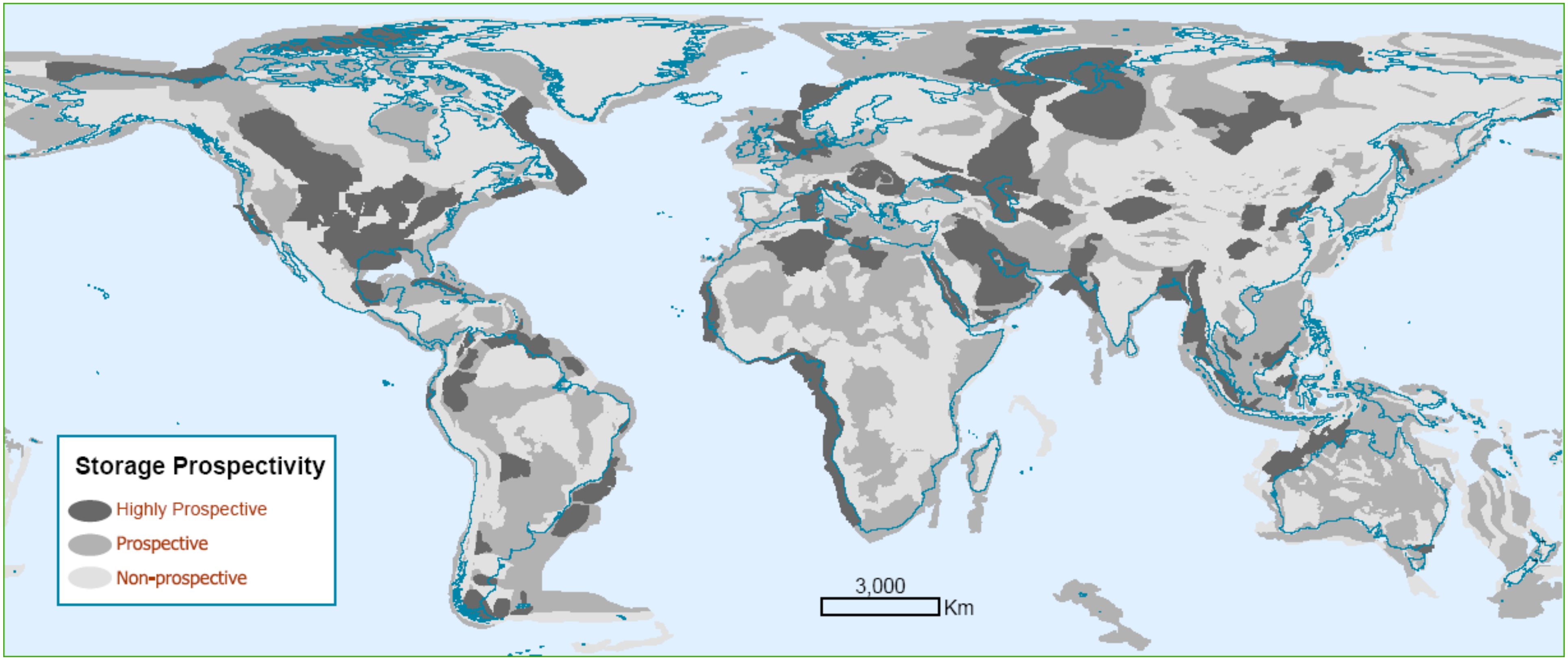


IPCC, 2005. Special Report on Carbon Dioxide Capture and Storage. Chapter 3.

Transportation: Key Issues

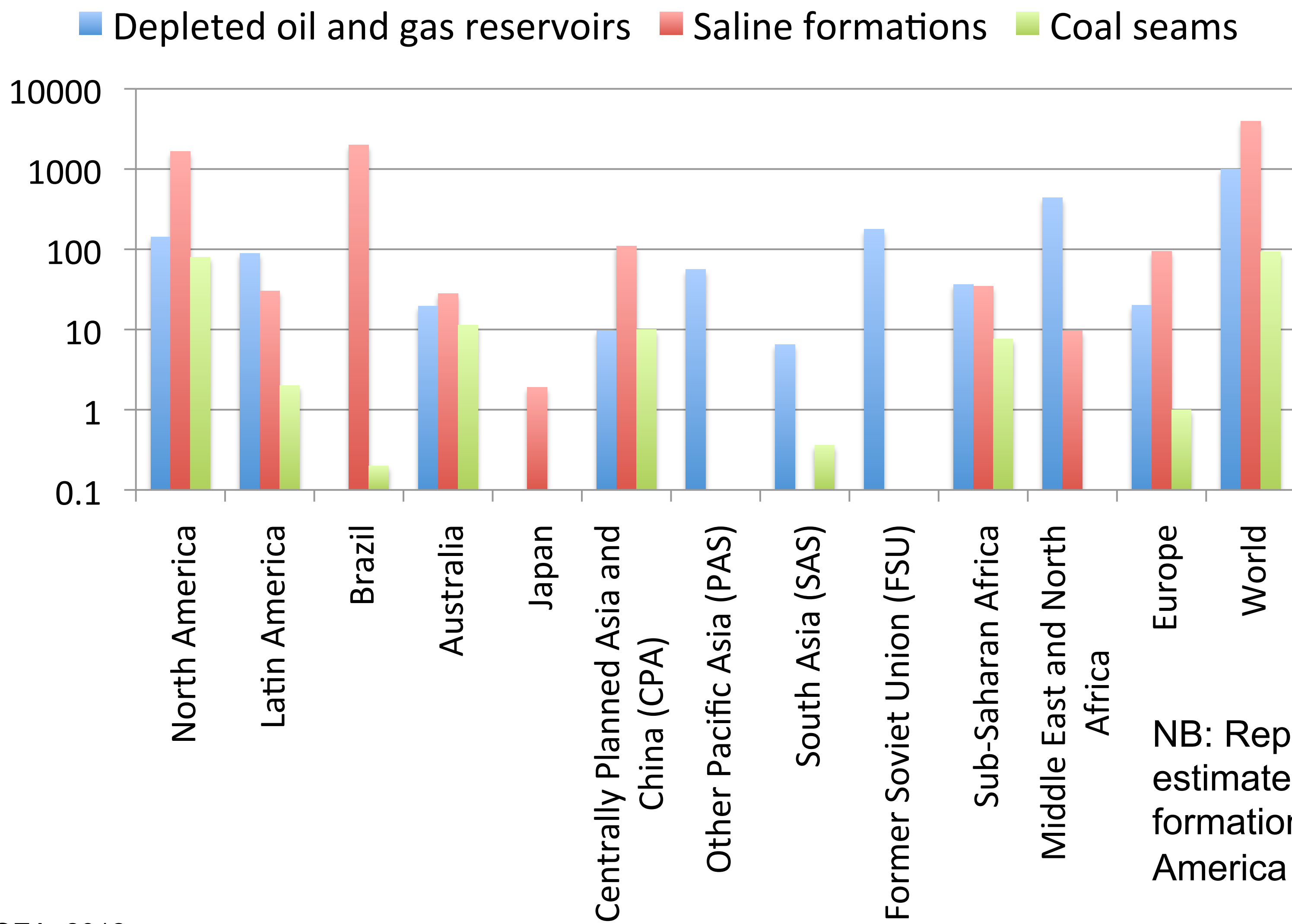
- Costs are highly scale dependent
  - Large returns with scale
- Long distance CO_2 transport unlikely without development of a common CO_2 pipeline system
  - Would help to piggyback on infrastructure developed for CCS with fossil fuels

Global Distribution of Prospective Sequestration Sites



Potential sequestration sites are broadly distributed around the globe.

Global Sequestration Capacity Estimates Billion Tonnes of CO_2



NB: Represents low estimates for Saline formations in North America

From KM13 GEA, 2012.

Storage: Key Issues

- In principle, no technical limitations to small scale storage
- But, major cost drivers are likely to be scale dependent (e.g. cost per tonne CO_2 will be greater for smaller projects)
  - Site characterization
  - Injection wells
  - Monitoring
- Institutional regulatory capacity to ensure and enforce safe and environmentally sound storage operations

Summary: Scalability of CCS

- BECCS influenced by issues of scale and implementation strategy

Capture | Transport | Storage

- CCS strategies and technologies tailored to bio-energy are needed
  - What are the most important areas to focus on?
- BECCS would benefit by taking advantage of a CCS infrastructure built to manage fossil fuel and industrial emissions

- Technology needs highly dependent on buildup of BECCS
  - Global biomass supply chain with large scale deployment
  - Availability of sustainably and reliably produced biomass feedstocks for 30-50 years
  - Local to regional biomass supply chain with small scale deployment
  - Co-location of geological storage resources with demand for electricity/heat and biomass resources
  - Ability to cost-effectively scale (up/down) each element in the BECCS technology chain

Enhanced Weathering and Other Routes

- Putting ground silicates onto land surface – kinetics?
- Biogeochemical activity in soil naturally accelerates weathering
- Aforestation/reforestation
- Forest and soil management – ecological limits and environmental impacts of implementation at scale
- Methods for Carbon Utilization

Considerations for NETs

- Limitations on the potential of each technology
  - interaction of the biochar with different soils, carbon sequestration, electricity demand obstacle to rollout, the need for abundant supplies of water, validation of costs, etc.

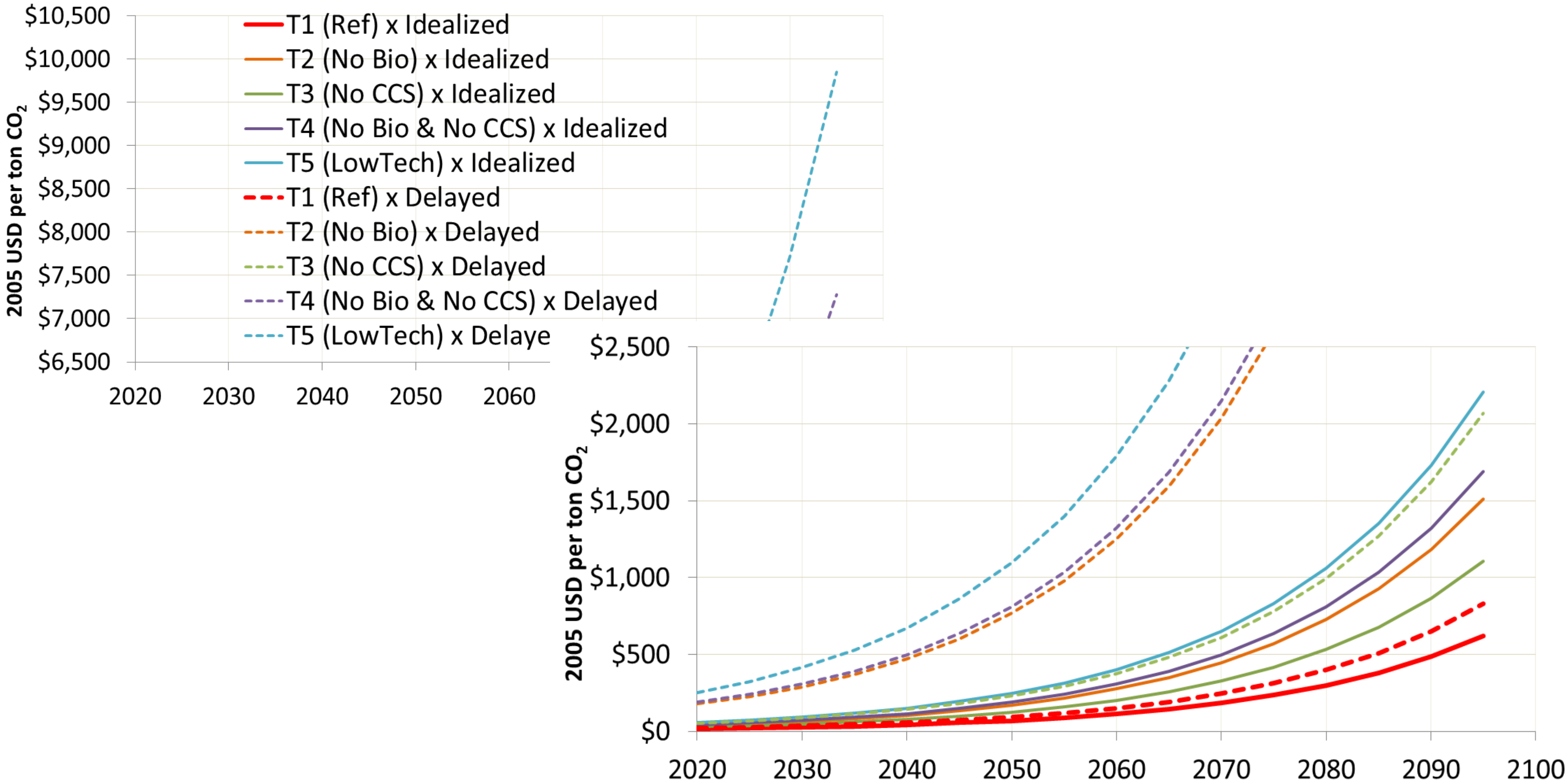
- The potential for unintended environmental or even climate consequences in the large scale deployment of these technologies

- Present costs are based on projections from non-commercial market price estimates – meaning that there is a substantial risk that negative emissions may not be cost competitive within a suite of mitigation options thereby negating their role on a least cost basis

- Issue of ‘moral hazard’ - by giving policy makers the excuse for not developing effective mitigation programs and low carbon technologies, less will be done to mitigate against climate change

See Grantham Institute for Climate Change Briefing paper No 8, Imperial College London, McGlashan et al., October 2012.

Achieving 2.6 W/m^2 without BECCS



Technology Set	CCS	Bioenergy	Nuclear Power	Other Technology
T1 (Ref)	Yes	Yes	Ref	Ref
T2 (NoCCS)	No	Yes	Ref	Ref
T3 (NoBio)	Yes	No	Ref	Ref
T4 (NoBio & No CCS)	No	No	Ref	Ref
T5 (LowTech)	No	No	Phased out	Ref

Global Annual GHG Emissions by Sector

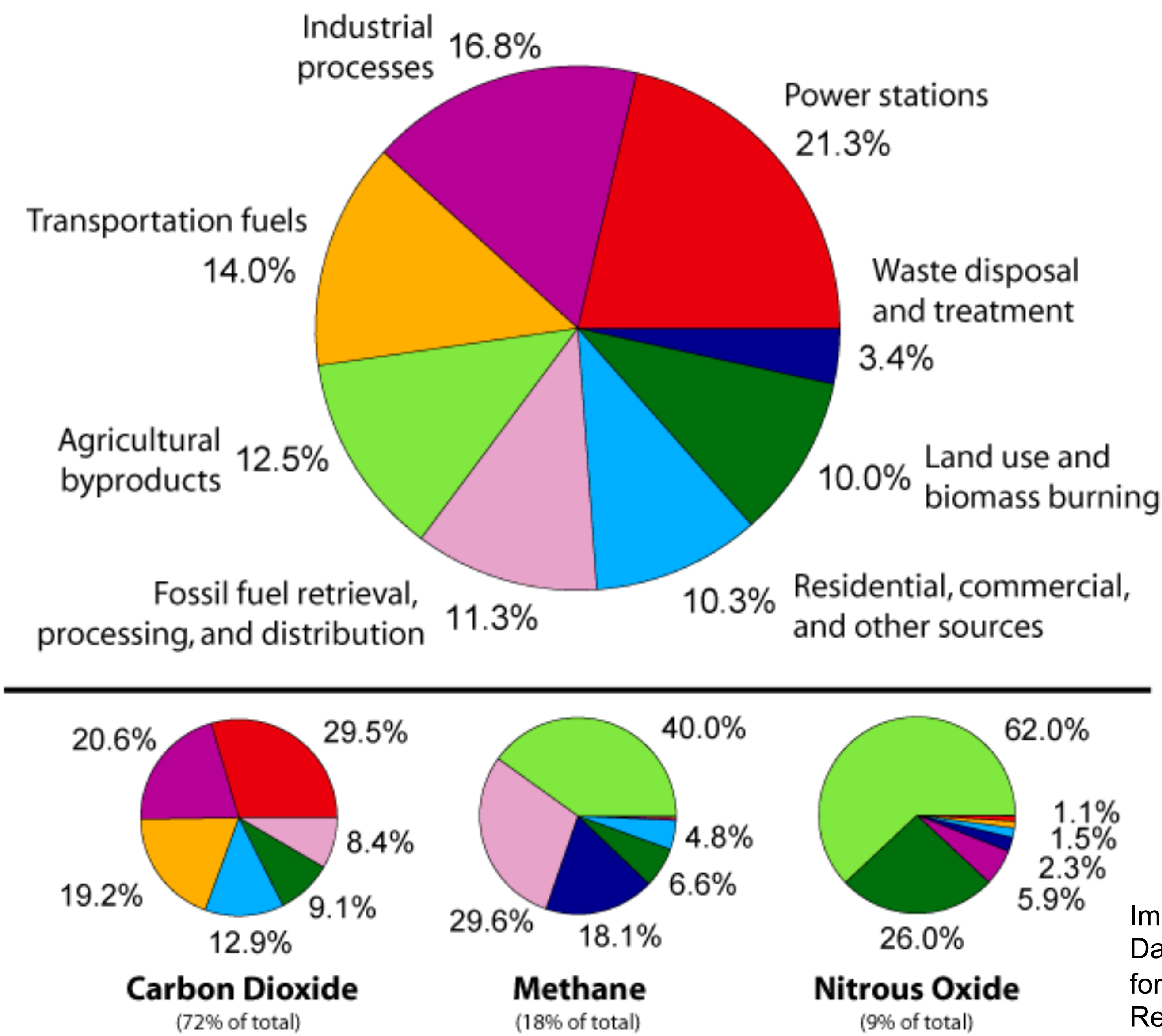


Image: Global Warming Art.
Data: Emission Database for Global Atmospheric Research 2000 project.

Non-CO_2 Emissions

- CH_4
- N_2O
- Ozone
- HFCs etc.
- Black Carbon

For More Information

- IPCC report
- Process Safety and Environmental Protection, Special Issue: Negative Emissions Technology, November 2012, Volume 90, Issue 6.
- Climatic Change – special issue on Negative Emissions, May 2013, Volume 118, Issue 1.
- Virgin Earth Challenge – go to "Links" and "Finalists"
- Initiative for Carbon Negative Energy
- International Institute for Applied Systems Analysis (IIASA)
- Global Carbon Project (GCP)

Past GCEP Workshop, Stanford, June 2012

Assessment Report from the GCEP Workshop on Energy Supply with Negative Carbon Emissions

Jennifer L. Milne[1] and Christopher B. Field[2]

Abstract

As part of its assessment towards energy technologies that reduce greenhouse gas (GHG) emissions, The Global Climate and Energy Project (GCEP) held a workshop at Stanford University on June 15, 2012, on the topic of Energy Supply with Negative Carbon Emissions. The workshop addressed 4 main topics: Biomass Energy with Negative Emissions; Carbon Capture, Conversion and Storage; Addressing Other Contributions to Carbon Emissions; and System Modeling. This report summarizes the discussion and highlights research needs that were identified at the workshop by speakers and participants. The unparalleled ability of biological systems to capture and cycle carbon, and the potential to use these systems as part of an energy supply that leads to negative emissions, was brought to the forefront at this workshop, as well as the need for integrated systems of supply, conversion and storage. Reaching net negative carbon emissions on a global scale could also be possible without the use of bioenergy with carbon capture and storage, but the predicted costs of carbon in these energy technology scenarios would be extraordinarily high. Studies aimed at understanding and overcoming the limits to technologies for bioenergy with negative emissions, identification of integrated and optimized systems for negative emissions, and research towards novel carbon storage technologies would represent groundbreaking steps towards technologies that could achieve net negative carbon emissions in our energy supply.

Key Findings

- Need for integrated and optimized systems – supply, conversion and storage
- Novel carbon storage technologies
- Understanding and overcoming limits to bioenergy with negative emissions

Proposals have been selected for funding

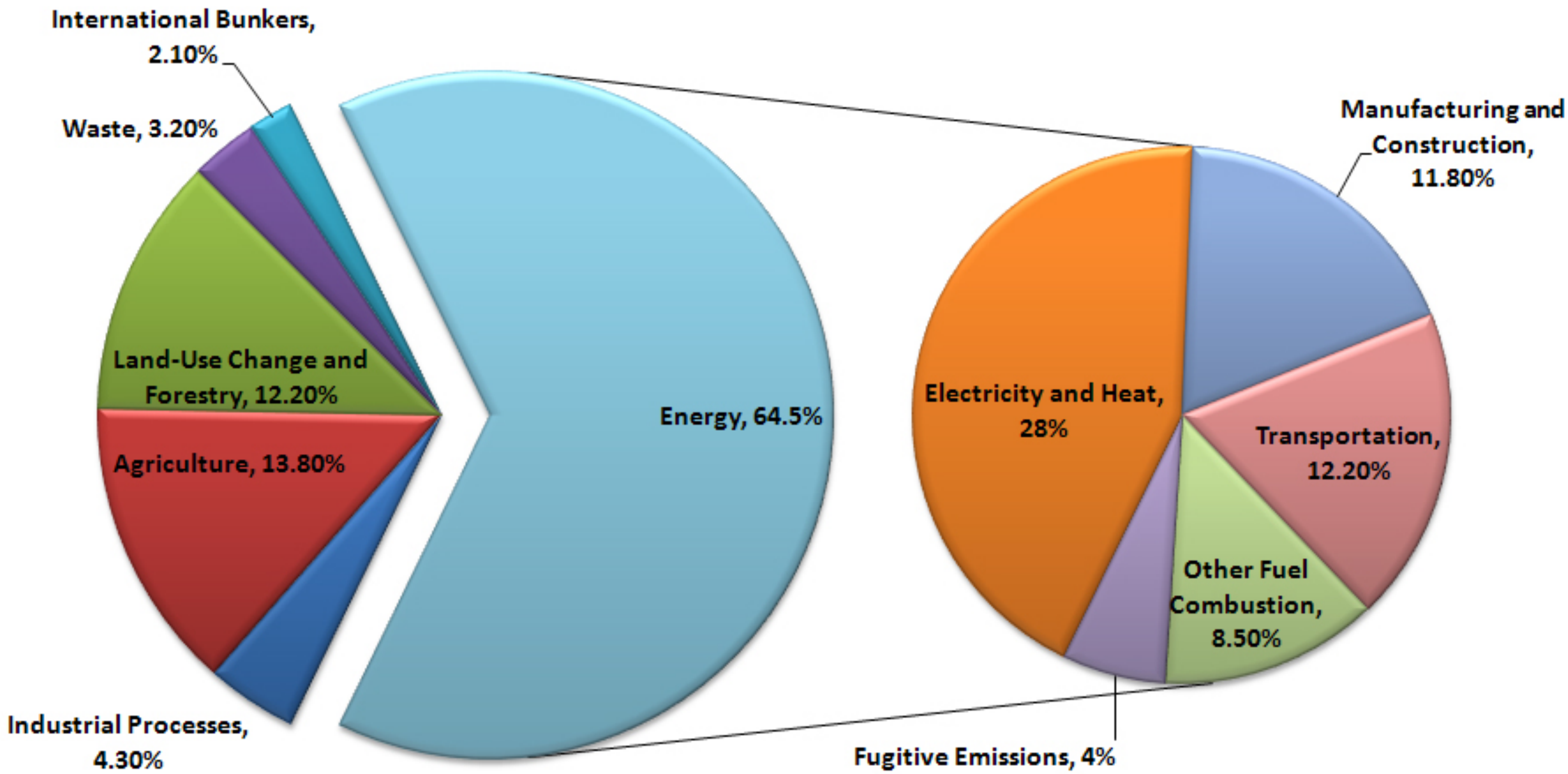
Thanks

Extra Slides

References

- Davis *et al*., Science, 2010.
- Grantham Institute for Climate Change Briefing paper No 8, Imperial College London, McGlashan *et al*., October 2012.
- McGlashan et al., Process Safety and Environmental Protection, November 2012.

Global Anthropogenic GHG Emissions by Sector 2005



Source: Climate Analysis Indicators Tool, World Resources Institute

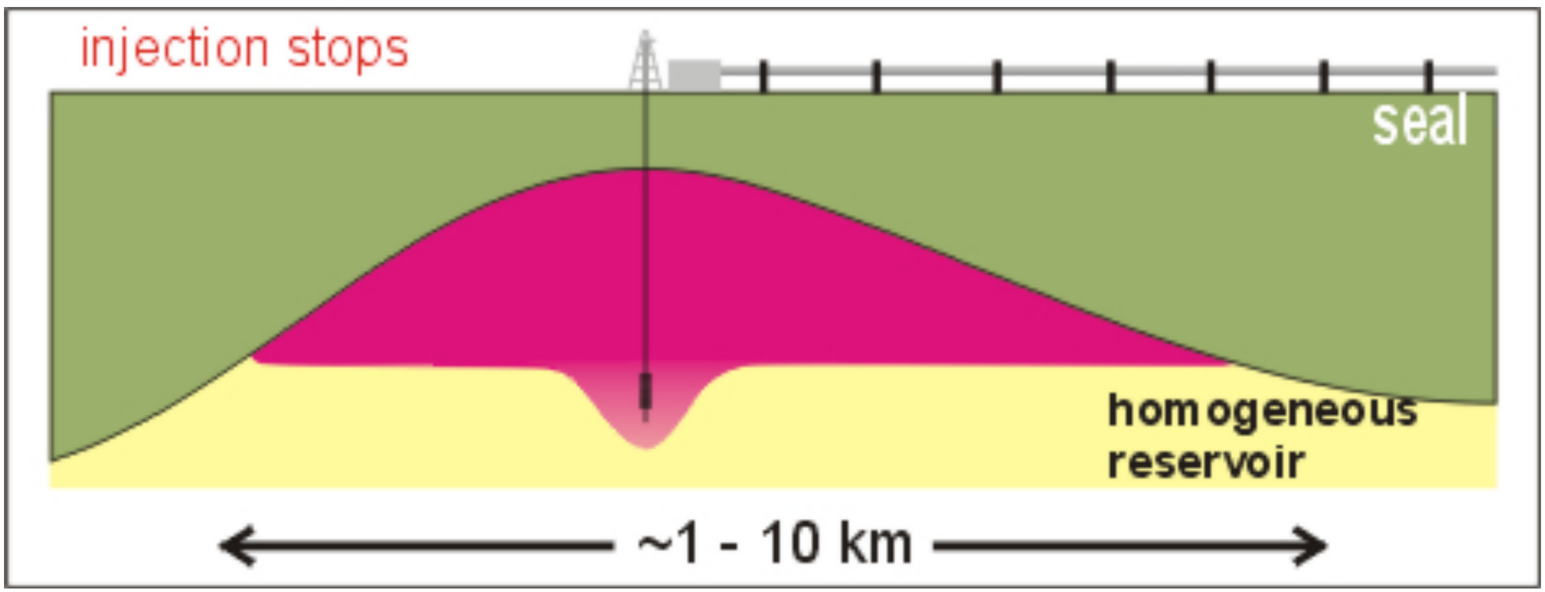
Global Sequestration Capacity Estimates

Region	Estimated Storage Capacity (billion tonnes of CO_2)				Source	Note
	Depleted Oil and Gas Reservoirs	Saline Formations	Coal Seams	TOTAL		
North America	143	1653-20,213	60-117	1856-20,473	1	
Latin America	89	30.3	2	NA	14	a
Brazil	NA	2000	0.2	2000.2	2	
Australia	19.6	28.1	11.3	59	3, 4	b
Japan	0	1.9-146	0.1	2-146.1	5, 6, 14	
Centrally Planned Asia and China (CPA)	9.7-21	110-360	10	1445 -3080	7, 8, 9, 17	c
Other Pacific Asia (PAS)	56-188	NA	NA	56-188	11, 12	d
South Asia (SAS)	6.5-7.4	NA	0.36-0.39	6.86-7.79	12	e
Former Soviet Union (FSU)	177	NA	NA	177	13	f
Sub-Saharan Africa	36.6	34.6	7.6	48.3	14	g
Middle East and North Africa	439.5	9.7	0	449.2	14	
Europe	20.22-30	95.72-350	1.08-1.5	117-381	15, 16	h
World	996 - 1150	3963 - 23,171	93 – 150			i

From KM13 GEA, 2012.

Basic Concept of Geological Sequestration of CO_2

- Injected at depths of 1 km or deeper into rocks with tiny pore spaces
- Primary trapping
  - Beneath seals of low permeability rocks



Courtesy of John Bradshaw

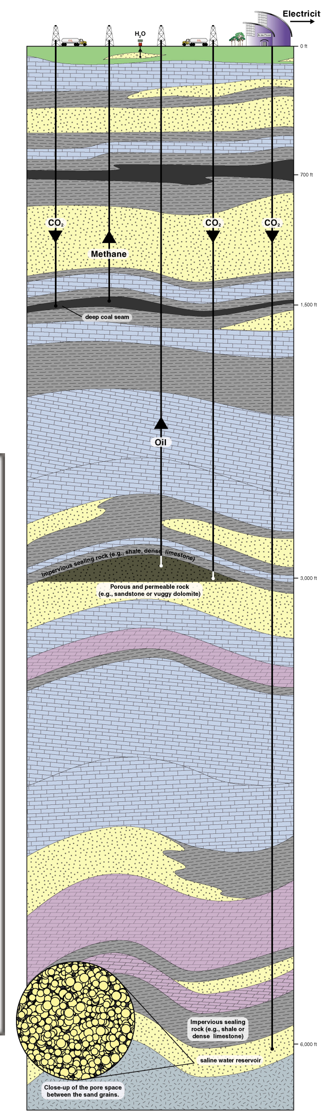


Image courtesy of ISGS and MGSC