

The Geoengineering Agenda

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**A briefing at the kickoff meeting
of the Committee on Geoengineering Climate:
Technical Evaluation and Discussion of Impacts**

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Key recommendation

Deliberate manipulation at a planetary scale raises profound issues.

The scrimmage line is *research*: slippery slope vs. mandate.

My principal recommendation: Geoengineering research should be embedded in normal science, not conducted separately.

This will provide quality control and encourage dual-purpose research.

It is essential to understand our planet more deeply. To create options to do geoengineering wisely is, for now, a subordinate reason for much stronger planetary science.

CDR and SRM

CDR and SRM are very different.

CDR: Slow (think -1 ppm/yr), planetary only, low risk, few deep issues

SRM: Fast, allows regional targets (e.g., arctic), high risk, high leverage, fundamentally new

Distribute *your* effort 10:90?

My talk is 60:40, reflecting what I have thought about.

Four World Views

		Are fossil fuels hard to displace?	
		NO	YES
Is climate change an urgent matter?	NO	A nuclear or renewables world unmotivated by climate.	Most people in the fuel industries and most of the public are here. 5°C.
	YES	Environmentalists, nuclear advocates are often here. 2°C.	YOUR WORKING ASSUMPTIONS? 3°C, tough job.

The Case for Carbon Dioxide Removal (CDR)

CDR can counter recalcitrant *decentralized* CO₂ emissions, such as emissions from buildings and vehicles, that prove expensive to reduce by other means.

CDR might someday enable the world to lower the atmospheric CO₂ concentration gradually.

CDR Strategies

Direct air capture (DAC) with chemicals

Biological strategies (Bio-CDR)

- Biopower with CCS (BECCS)

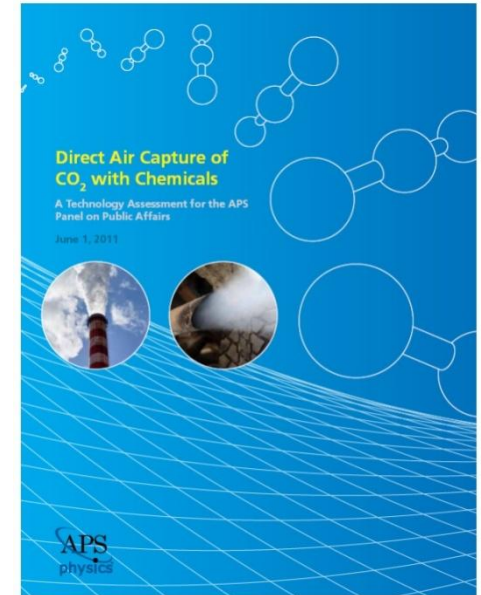
- Afforestation

- Ocean fertilization

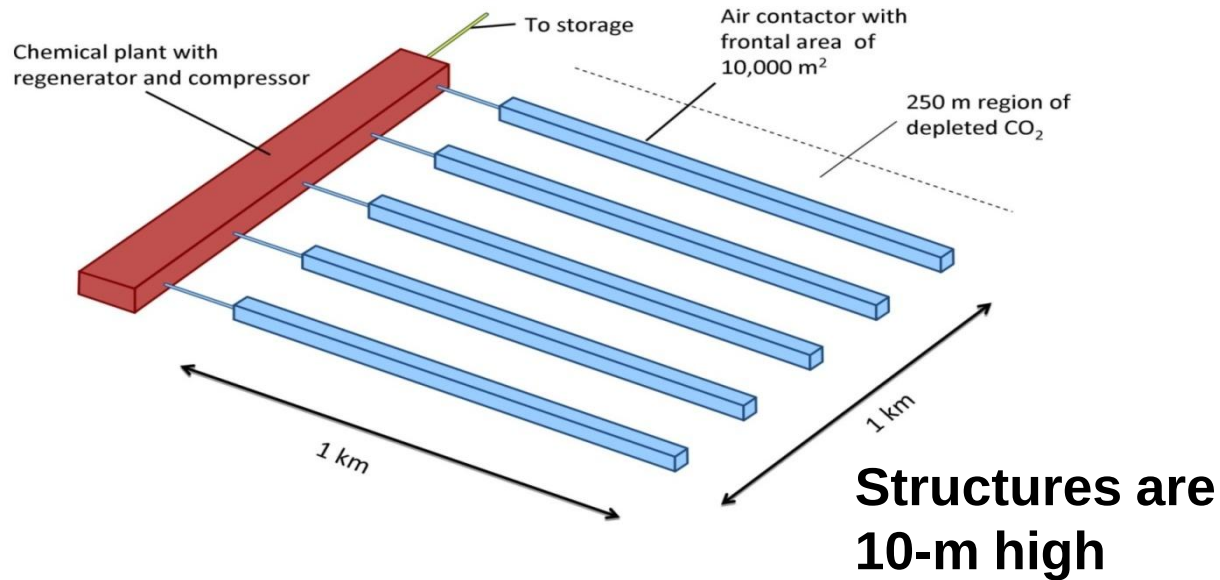
Chemical strategies

- Ocean alkalinity

- Enhanced weathering



Scale for DAC



A 1 MtCO₂/yr system (50% capture, 2 m/s air velocity)

Six of these compensate for a 1 GW coal plant. All 30 structures end-to-end make a 30-km Great Wall.

Research frontier: Is 250 meter spacing adequate? The downstream intake must not entrain depleted air.

DAC research: materials and systems

Priority areas include:

- Strategies for bringing air into contact with chemicals

- New chemistries for sorption and regeneration

- Materials that can operate effectively and efficiently over tens of thousands of consecutive cycles

DAC research will almost surely lower the cost of post-combustion capture of CO₂ from industrial facilities.

The off-ramp to synfuels from DAC

In most cases the cost of fuels from CO₂ is dominated by the cost of hydrogen. But if CO₂ from DAC costs hundreds of dollars per ton, hydrogen and CO₂ costs are comparable.

Side calculation: At what cost of CO₂ does it contribute as much to the cost of synfuels as \$2/kgH₂?

H₂ at \$2/kgH₂ is matched to 6 ¢/kWh power, 100% efficient electrolysis

Note: \$2/kgH₂ ≈ \$2/gal gasoline-eq,

Use $3 \text{ H}_2 + \text{CO}_2 \rightarrow \text{CH}_4 + 2 \text{ H}_2\text{O}$ (CH₄ ≈ gasoline, diesel)

Answer: **\$270/(t CO₂).**

Note: Same answer for methanol.

In short, each \$140/tCO₂ and each 3¢/kWh contributes \$1/gallon to the feedstock cost of synfuels.

Message about DAC: First things first

It will almost surely be much cheaper to capture CO₂ from the flue gas of a coal power plant than from ambient air, where it is 300 times more dilute. At a natural gas plant, 100 times.

Accordingly, aggressive deployment of DAC makes little sense until the world has largely eliminated *centralized and concentrated* sources of CO₂ emissions, especially at coal and natural gas power plants:

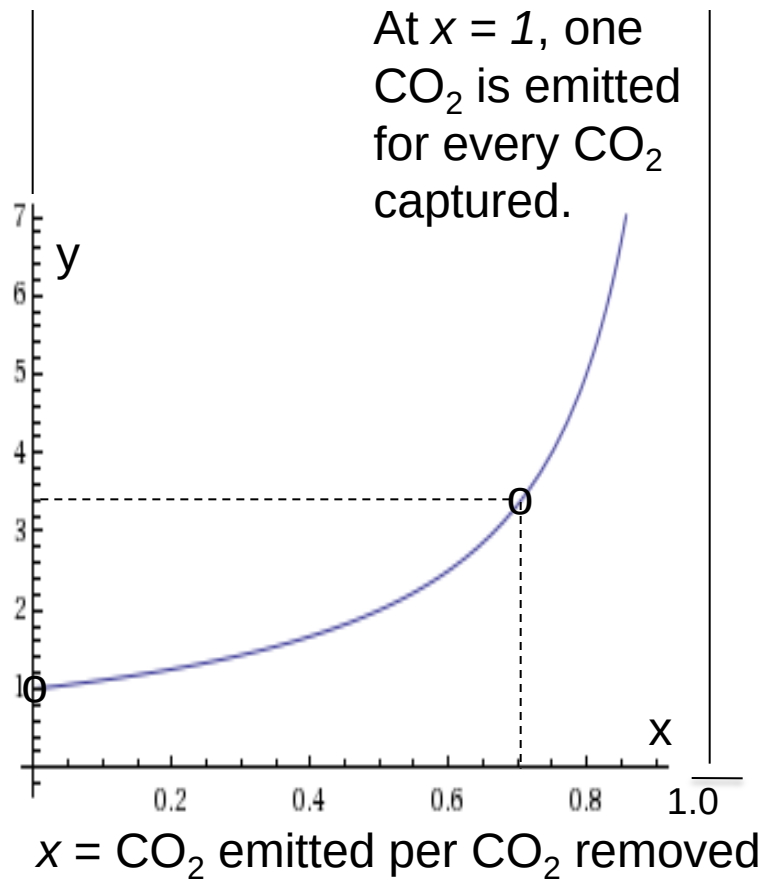
- by efficiency gains that make the plants unnecessary
- by substitution of non-fossil alternatives
- by capture of nearly all of the plants' CO₂ emissions.

“Net-carbon” raises CDR cost \$/(tCO₂ no longer in the atmosphere)

The cost-multiplier, y , is the ratio of avoided cost to capture cost:

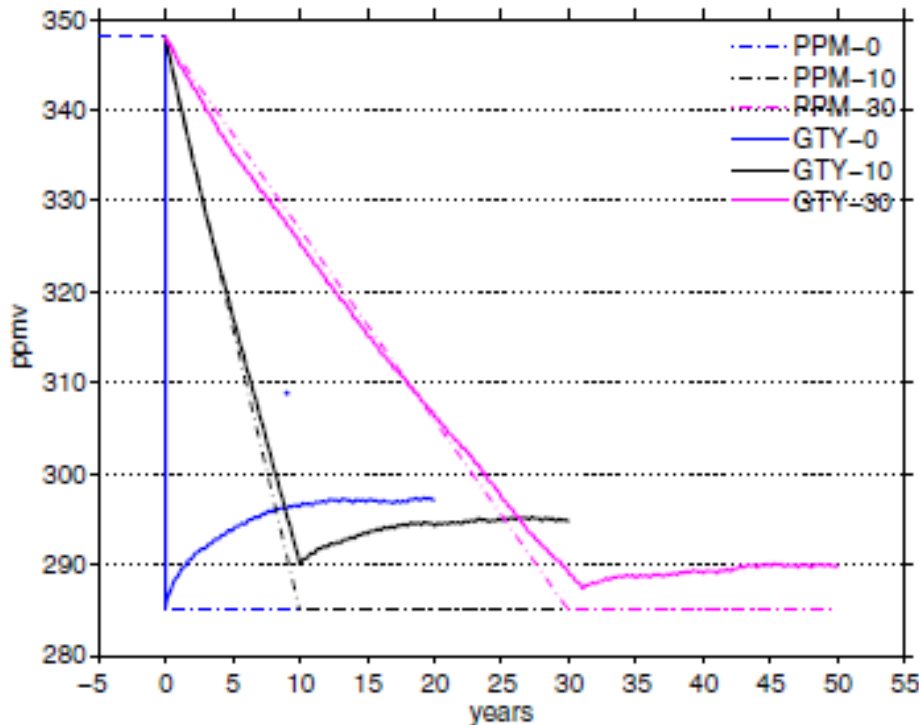
$$y = 1/(1 - x),$$

where x is the amount of CO₂ emitted per CO₂ captured.



Example: the APS benchmark system has $x = 0.3$. Grid power runs the fans and compressor, but regeneration heat is provided by natural gas with CCS. Without CCS, $x = 0.7$.

Research frontier: Negative feedbacks for CDR



M. Vichi, A. Navarra, P.G. Fogli.
2013. "Adjustment of the natural
carbon cycle to negative emission
rates." *Climatic Change*.

<http://rd.springer.com/article/10.1007/s10584-012-0677-0>

Above: Six scenarios where ocean outgassing accompanies CDR. Expect land feedbacks too (carbon defertilization).

"Takeback": Conservatively, to reduce the mass of CO₂ in the atmosphere by one ton, one must remove ≈ 2 tons.

Immense land requirements for Bio-CDR

The bio-CDR strategies, and indeed all versions of bio-mitigation, make immense demands on land.

Side calculation (see Smith & Torn): Land for afforestation to reduce atmospheric CO₂ concentration by 1 ppm/yr (for 50 years). Assume:

10 t biomass/ha-yr (for 50 years), 0.5 tC/t biomass, so **5 tC/ha-yr**

1 ppm = 2 GtC, so must remove **4 GtC/yr** if ocean and land feedback is 50%.

Result: **800 Mha.** (US area: 1000 Mha)

Similar answer for BECCS: Twice the yield (20 t biomass/ha-yr, indefinitely) but, net, only 50% of captured carbon is sequestered.

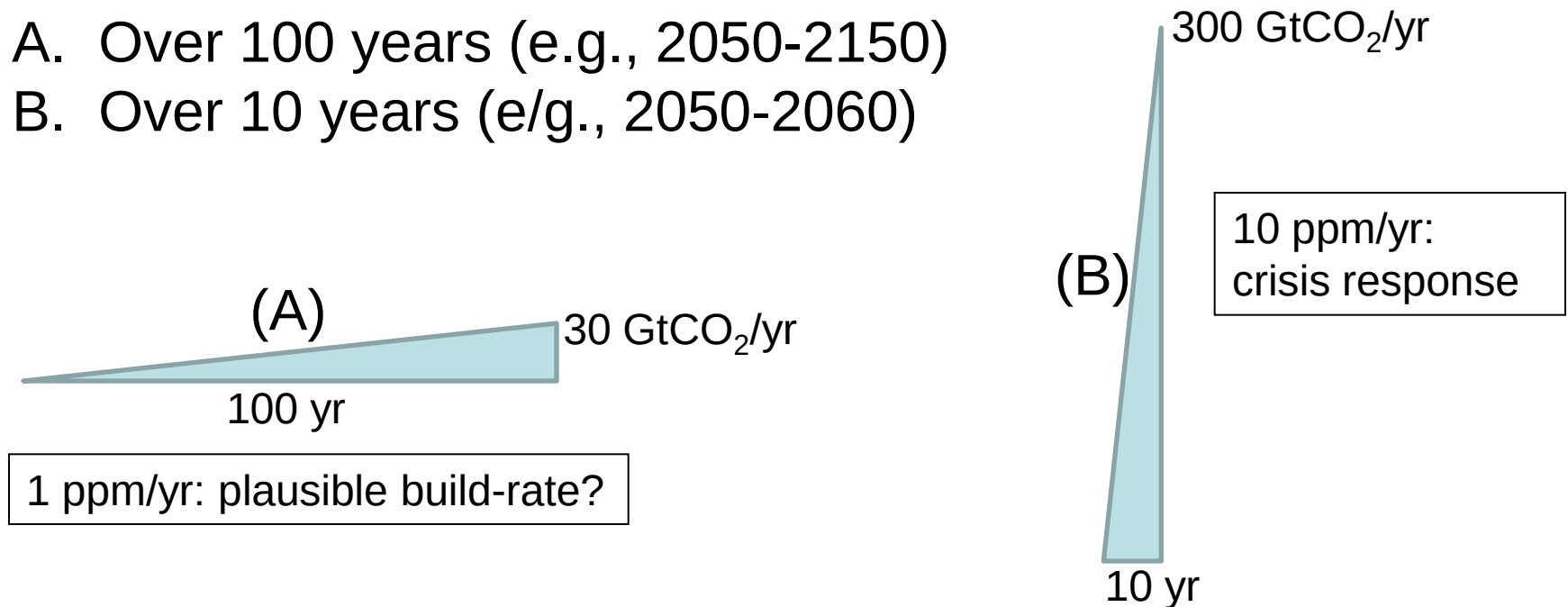
Compare to 1.5 Mha for DAC (15,000 of the 1 km x 1 km facilities in the earlier slide), neglecting net-carbon issues and land for storage.

CDR: not matched to emergencies

Lower the CO₂ concentration by **100 ppm** (capture **1500 GtCO₂**):

A. Over 100 years (e.g., 2050-2150)

B. Over 10 years (e.g., 2050-2060)



“Pace” (slope, rate of increase in removal capability):

(A) 0.30 GtCO₂/yr²; (B) 30 GtCO₂/yr² (100 times larger).

The pace in (B) is far too fast for CDR. It is equivalent to canceling the entire global fossil-fuel system in one year.

CDR research that you might recommend

1. Ecological and social evaluation of the competition for land among biocarbon strategies (BECCS, afforestation, biofuels, and conventional biopower) and between them and forest products and food.
2. Cost estimation for low-carbon strategies in a world with high carbon prices (think \$200/tCO₂): e.g., DAC vs. natural gas with 99%-CCS vs. advanced heat pumps, 100 mpg cars and biopowered airplanes.
3. Materials and cycles for CO₂ capture from gas mixtures (relevant to CCS and DAC).

The case for Solar Radiation Management (SRM): What if the current technocratic response is insufficient?

The unfolding technological response to climate change may turn out to be insufficient for two very different reasons:

1. The world cannot implement the necessary changes.
 - A. Inertia and habit
 - B. Vested interests – incumbent political power
 - C. Shortcomings of the available “solutions”
2. The world *does* implement the necessary changes, but low-probability nasty outcomes arrive anyway.

Monsters behind the door

Steve Pacala calls the worst credible climate outcomes “monsters behind the door.” The monsters include:

- a three-meter rise in sea level by the end of this century

- major alterations of the global hydrological cycle

- major changes in forest cover

- major emissions of greenhouse gases from the tundra.

The monsters open their door in a world of strong positive feedbacks, a world that spirals out of control.

Might your committee recommend that a greater fraction of earth-systems science R&D (field, lab, and modeling) be devoted to low-probability high-consequence outcomes?

Initiating an SRM intervention

We may someday need “fast geoengineering,” matched to the sudden onset of a crisis. S injection acts quickly.

The analogy here is to the use of epinephrine to treat an acute allergic reaction. It is considered irresponsible for a doctor not to have epinephrine in his or her medicine cabinet.

But geoengineering today is “comparable with 19th century medicine.” (James Lovelock).

Moreover, we need to think hard about how an “emergency” will be identified and how interventions will be implemented. (See Novim report.)

Ending an SRM intervention

Rapid disengagement from S-injection might be:

- a. deliberate: an adverse side-effect is discovered;
- b. unintentional: loss of capability, political will.

In one model run, following an interruption of injection, “within a few decades, winter warming in the polar regions exceeds 10°C and summer warming in the northern temperate latitudes will be about 6°C.”

“Coming generations will have to live with the danger of this ‘Sword of Damocles’ scenario, the abruptness of which has no precedent in the geologic history of climate.”

SRM research: at what scale?

Is there a scale large enough so that research can tell us what we need to know but small enough not to trigger the hazards we must avoid?

The testing of therapeutic drugs confronts this question too.

Do we already have sufficient safeguards to embed small-scale SRM research in normal science? How small is “small”?

Can large-scale “research” be forbidden by international agreement?

Chronic SRM

If R&D suggests that SRM can be done safely, there will be a separate argument over “chronic” SRM, e.g., SRM that maintains -1 W/m^2 of negative forcing indefinitely, without reference to emergencies.

Chronic SRM would reduce warming and provide learning. But it would take us further down the slippery slope.

The case for putting 90% of your effort into SRM

1. Science today can't exclude outcomes with terrible consequences ("monsters behind the door"). Soon, more science will be aimed at these monsters.
2. Interventions that address these monsters might be developed. They do not yet exist. Some may be SRM interventions. CDM acts too slowly to be relevant.
3. Interventions, including SRM-type, raise new issues:
 - A. What constitutes an emergency?
 - B. What criteria (safety, equity,...) should be used to allow an intervention?
 - C. What R&D might lead to usable interventions?

Our moral responsibility

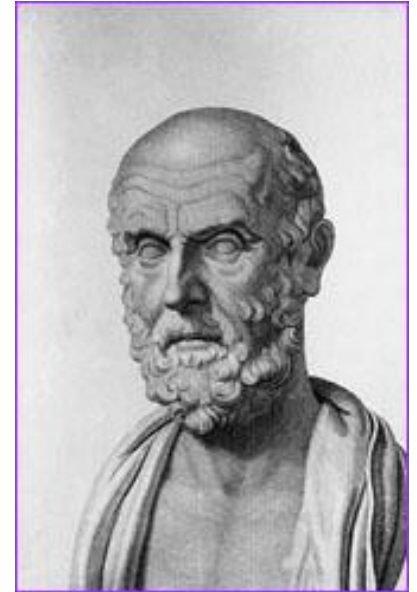
The various publics concerned about climate change want CDR and SRM to be available, inexpensive, and risk-free.

It is obligatory, therefore, for experts (including this committee) not to create false hopes – in this case, not to allow our audiences to infer that humanity can “solve” climate change while being relaxed about fossil fuels.

Patient Earth

“I will apply, for the benefit of the sick, all measures that are required, avoiding those twin traps of overtreatment and therapeutic nihilism.”

Hippocrates



* Modern version of the Hippocratic oath, Louis Lasagna, 1964,
http://www.pbs.org/wgbh/nova/doctors/oath_modern.html

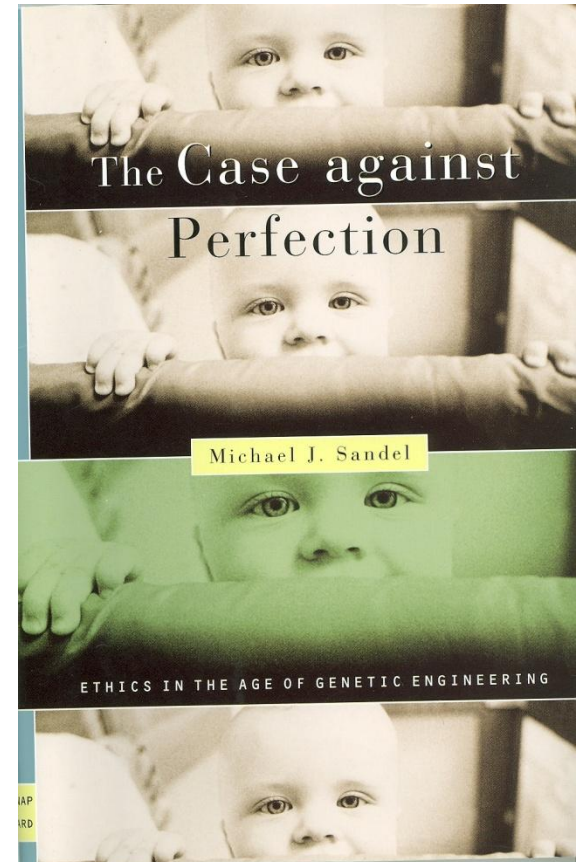
Extra Slides

Geoengineering as enhancement

Geoengineering will allow enhancement of the planet, much as genetic engineering now allows enhancement of the human species

Michael Sandel, in *The Case Against Perfection*, argues that genetic enhancement can be pursued to excess. He sees a loss of the ability to savor the life we have been “gifted.” He sees value in randomness, the “unbidden.”

A similar deep critique of geoengineering can be expected.



“When science moves faster than moral understanding, as it does today, men and women struggle to articulate their unease.”

Acronyms

APS: American Physical Society

BECCS: Biological energy with carbon capture and storage

Bio-CDR: Carbon dioxide removal from the atmosphere via biology

CCS: Carbon dioxide capture and storage

CDR: Carbon dioxide removal from the atmosphere

DAC: Direct air capture of CO₂ (via inorganic chemicals, not biology)

R&D: Research and development

SRM: Solar radiation management (by changing the earth's albedo)

CDR and SRM References

“Modeling meets science and technology: An introduction to a Special Issue on Negative Emissions,” M Tavoni and R Socolow, *Climatic Change*, Vol 118, Issue 1, May 2013, pp. 1-14

“Ecological limits to terrestrial biological carbon dioxide removal,” L Smith and M Torn. *Climatic Change*, Vol 118, Issue 1, May 2013, pp. 89-103

“Adjustment of the natural carbon cycle to negative emission rates,” M Vichi, A Navarra, P Fogli. *Climatic Change*, Vol 118, Issue 1, May 2013, pp. 105-118

“Direct air capture of CO₂ with chemicals: optimization of a two-loop hydroxide-carbonate system using a countercurrent air-liquid contactor,” M Mazzotti, R Baciocchi, M Desmond, R Socolow. *Climatic Change*, Vol 118, Issue 1, May 2013, pp. 109-135

[Direct Air Capture of CO₂ with Chemicals A Technology Assessment for the APS Panel on Public Affairs, June 1, 2011](http://www.aps.org/policy/reports/assessments/index.cfm). R. Socolow et al.
<http://www.aps.org/policy/reports/assessments/index.cfm>

J. J. Blackstock, D. S. Battisti, K. Caldeira, D. M. Eardley, J. I. Katz, D. W. Keith, A. A. N. Patrinos, D. P. Schrag, R. H. Socolow and S. E. Koonin, [Climate Engineering Responses to Climate Emergencies](#) (Novim, 2009).

Special issue: Science and Policy of Negative Emission Technologies

***Climatic Change*: Volume 118, Issue 1, May 2013**

Hyperlinks to the ten papers (1 of 2)

1. CLIM-D-12-00647 Modeling meets science and technology: An introduction to a Special Issue on Negative Emissions. Tavoni and Socolow.

<http://rd.springer.com/article/10.1007/s10584-013-0757-9/fulltext.html>

2. CLIM-D-12-00193 The role of negative CO₂ emissions for reaching 2°C - Insights from Integrated Assessment Modelling. van Vuuren et al.

<http://rd.springer.com/article/10.1007/s10584-012-0680-5>

3. CLIM-D-12-00108R1 Can Radiative Forcing Be Limited to 2.6 Wm⁻² Without Negative Emissions From Bioenergy and CO₂ Capture and Storage? Edmonds et al.

<http://rd.springer.com/article/10.1007/s10584-012-0678-z>

4. CLIM-D-12-00194R1 Is atmospheric carbon dioxide removal a game changer for climate change mitigation? Kriegler et al. <http://rd.springer.com/article/10.1007/s10584-012-0681-4>

5. CLIM-D-12-00181R2 Direct Air Capture of CO₂ and Climate Stabilization: A Model Based Assessment. Chen and Tavoni. <http://rd.springer.com/article/10.1007/s10584-013-0714-7>

Special issue: Science and Policy of Negative Emission Technologies

***Climatic Change*: Volume 118, Issue 1, May 2013**

Hyperlinks to the ten papers (2 of 2)

6. CLIM-D-12-00115R1 Optimal mitigation strategies with negative emission technologies and carbon sinks under uncertainty. Fuss et al.

<http://rd.springer.com/article/10.1007/s10584-012-0676-1>

7. CLIM-D-12-00243 Ecological limits to terrestrial biological carbon dioxide removal. Smith and Torn. <http://rd.springer.com/article/10.1007/s10584-012-0682-3>

8. CLIM-D-12-00179R1 Adjustment of the natural carbon cycle to negative emission rates. Vichi et al. <http://rd.springer.com/article/10.1007/s10584-012-0677-0>

9. CLIM-D-12-00190R1 Direct air capture of CO₂ with chemicals: optimization of a two-loop hydroxide-carbonate system using a countercurrent air-liquid contactor. Mazzotti et al. <http://rd.springer.com/article/10.1007/s10584-012-0679-y>

10. CLIM-D-12-00234 Exploring negative territory: Carbon dioxide removal and climate policy initiatives. Meadowcroft. <http://rd.springer.com/article/10.1007/s10584-012-0684-1>

Additional papers by presenter

["Truths We Must Tell Ourselves to Manage Climate Change"](#), by Robert H. Socolow, *Vanderbilt Law Review*, Vol. 65, Number 6, pp.1455-1478

["High-consequence outcomes and internal disagreements: tell us more, please,"](#) Robert H. Socolow, *Climatic Change*, August 9, 2011,.

["Balancing Risks: Nuclear Energy & Climate Change,"](#) Robert Socolow and Alexander Glaser..*Dædalus*. September 2009 138(4), 31-44.

"Beneficial Biofuels - The Food, Energy, and Environment Trilemma," Tilman, D, R Socolow, J Foley, J Hill, E Larson, L Lynd, S Pacala, J Reilly, T Searchinger, C Somerville, R Williams. *Science*, Vol. 325. no. 5938, pp. 270 – 271, July 17, 2009.

["Sharing Global CO₂ Emission Reductions Among One Billion High Emitters,"](#) Chakravarty, S, A Chikkatur, H de Coninck, S Pacala, R Socolow, and M Tavoni. *Proceedings of the National Academy of Sciences*, 2009: 106(29), 11884-11888.

["Good Enough Tools for Global Warming Policy Making,"](#) Robert H. Socolow and Sau-Hai Lam. *Philosophical Transactions of the Royal Society*, 365: 897-934, February 2007.

["A Plan to Keep Carbon in Check,"](#) Robert Socolow and Stephen Pacala. *Scientific American*, Vol. 295, No. 3, pp. 50-57, September 2006..

["Can We Bury Global Warming,"](#) Robert H. Socolow, *Scientific American*, July 2005, pp. 33-40.

["Stabilization Wedges: Solving the Climate Problem for the Next 50 Years with Current Technologies,"](#) S. Pacala and R. Socolow, *Science*, Vol. 305, pp. 968-972, August 13, 2004.