Negative Emissions Technologies and Reliable Sequestration: A Research Agenda

Stephen Pacala (Chair)
Princeton University
Reduce Carbon Sources

- Energy efficiency
- Low or zero-carbon fuel sources

Enhance Carbon Sinks

Negative emissions technologies: remove carbon dioxide from atmosphere and store it on or underneath Earth’s surface

- Coastal blue carbon
- Terrestrial carbon removal and sequestration
- Bioenergy with carbon capture and sequestration (BECCS)
- Direct air capture
- Carbon mineralization
- Geologic sequestration
Rationales for development and deployment of NETs

1. Reduce carbon pollution (i.e. 45Q tax credit in FUTURE Act)

2. Reduce climate change

3. Economic competitiveness and technological leadership
How large is potential market for NETs likely to be?
Or equivalently, how much carbon uptake is needed to meet Paris Agreement goals?

![Graph showing GHG emissions (GtCO₂/year) from 2010 to 20100 with annotations for Business as usual, Below 2°C, CO₂, Net zero GHG emissions, Gross negative CO₂ emissions, and Net negative GHG emissions.]

~10 GtCO₂/y globally by midcentury
~20 GtCO₂/y globally by the century’s end

UNEP, 2017
Rationales for development and deployment of NETs

1. Reduce carbon pollution (i.e. 45Q tax credit in FUTURE Act)

2. Reduce climate change

3. Economic competitiveness and technological leadership

4. Control carbon pollution/climate change with less decrease in fossil fuel use
For example…. Commercial Aviation

<table>
<thead>
<tr>
<th>Option 1: Develop Cellulosic Biofuels</th>
<th>Could be expensive and requires land to grow feedstock</th>
</tr>
</thead>
<tbody>
<tr>
<td>Option 2: Capture and store 10 kg of atmospheric CO$_2$ with a NET for each gallon of fossil fuel consumed</td>
<td>If this cost $100/tCO$_2$ then the offset would cost an additional $1.00/gallon</td>
</tr>
</tbody>
</table>
Study Motivation

• 2015 National Academies report recommends R&D investment to improve methods of CDR and sequestration at scales that matter, in particular to:
  – minimize energy and materials consumption
  – identify and quantify risks
  – lower costs
  – develop reliable sequestration and monitoring

• Need for **detailed** research and development agenda to assess benefits, risks, and sustainable scale potential; and increase commercial viability

• Sponsors: DOE, NOAA, EPA, USGS, V. Kann Rasmussen Foundation, Incite Labs, NAS, Linden Trust for Conservation
Statement of Task

• Identify the most urgent unanswered scientific and technical questions needed to:
  – assess the benefits, risks, and sustainable scale potential for carbon dioxide removal and sequestration approaches in terrestrial and coastal environments
  – increase the commercial viability of carbon dioxide removal and sequestration

• Define the essential components of a research and development program and specific tasks required to answer these questions

• Estimate the costs and potential impacts of such a research and development program to the extent possible in the timeframe of the study

• Recommend ways to implement such a research and development program
Committee Members

- Stephen Pacala (NAS), Chair, Princeton University
- Mahdi Al-Kaisi, Iowa State University
- Mark Barteau (NAE), Texas A&M University
- Erica Belmont, University of Wyoming
- Sally Benson, Stanford University
- Richard Birdsey, Woods Hole Research Center
- Dane Boysen, Modular Chemical Inc.
- Riley Duren, Jet Propulsion Laboratory
- Charles Hopkinson, University of Georgia
- Christopher Jones, Georgia Institute of Technology
- Peter Kelemen (NAS), Columbia University
- Annie Levasseur, École de Technologie Supérieure
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- Jennifer Wilcox, Worcester Polytechnic Institute

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- John Holmes, Board on Energy and Environmental Systems
- Yasmin Romitti, Board on Atmospheric Sciences and Climate
- Anne Linn, Board on Earth Sciences and Resources
- Emily Twigg, Ocean Studies Board
- Camilla Ables, Board on Agriculture and Natural Resources
- Anna Sberegaeva, Board on Chemical Sciences and Technology
Study Process

- Information gathering workshops
  - Coastal Blue Carbon Approaches (July 2017)
  - Bioenergy with Carbon Capture and Storage Approaches (Oct. 2017)
  - Direct Air Capture (Oct. 2017)
  - Geologic Sequestration and Mineral Carbonation Approaches (Nov. 2017)

- Additional webinars and presentations
- Committee meetings to develop report
- Extensive external peer review
Negative Emissions Technologies

- Coastal blue carbon
- Terrestrial carbon removal and sequestration
- Bioenergy with carbon capture and sequestration (BECCS)
- Direct air capture
- Carbon mineralization
- Geologic sequestration
Four NETs are ready for large-scale deployment:

• afforestation/reforestation
• forest management
• uptake and storage by agricultural soils
• bioenergy with carbon capture and sequestration (BECCS)

However, additional research is likely to further reduce costs, increase efficiency and reduce unwanted impacts
• Safe and economical direct air capture or carbon mineralization would have essentially unlimited capacity to remove carbon
  – Direct air capture currently limited by high cost
  – Carbon mineralization currently limited by lack of fundamental understanding

• Blue carbon has capacity that is less than the other options, but potentially very low incremental cost given large co-benefits
<table>
<thead>
<tr>
<th>Negative Emissions Technology</th>
<th>Estimated Cost ($/tCO₂)</th>
<th>Upper Bound* for Safe* Potential Rate of CO₂ Removal Possible Given Current Technology and Understanding and at &lt; $100/tCO₂ (GtCO₂/y)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>L = 0-20</td>
<td>US</td>
</tr>
<tr>
<td>Coastal blue carbon</td>
<td>L</td>
<td>0.02</td>
</tr>
<tr>
<td>Afforestation/Reforestation</td>
<td>L</td>
<td>0.15</td>
</tr>
<tr>
<td>Forest management</td>
<td>L</td>
<td>0.1</td>
</tr>
<tr>
<td>Agricultural soils</td>
<td>L to M</td>
<td>0.25</td>
</tr>
<tr>
<td>BECCS</td>
<td>M</td>
<td>0.5</td>
</tr>
<tr>
<td>Direct air capture</td>
<td>H</td>
<td>0</td>
</tr>
<tr>
<td>Carbon mineralization</td>
<td>M to H</td>
<td>unknown</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>1.02</td>
</tr>
</tbody>
</table>

* Upper bound assumes full adoption of agricultural soil conservation practices, forestry management practices, and waste biomass capture.

*Safes means without without large-scale land-use change that could adversely affect food availability and biodiversity.
Recommendation: The nation should launch a substantial research initiative to advance negative emissions technologies as soon as practicable:

(1) improve coastal blue carbon, afforestation/reforestation, changes in forest management, uptake and storage by agricultural soils, and BECCS to increase capacity and to reduce negative impacts and costs

(2) make rapid progress on direct air capture and carbon mineralization technologies, which are underexplored but would have essentially unlimited capacity if high costs and many unknowns could be overcome

(3) advance NET-enabling research on biofuels and carbon sequestration that should be undertaken anyway as part of an emissions mitigation research portfolio
### Elements of Research Agenda

- NET and NET-enabling research
- Basic science and engineering research, development, demonstration, deployment
- For each research effort:
  - budget estimates
  - potential sponsors
  - timespan
  - gaps addressed

In many cases, research should be conducted in stages—funding will continue if certain milestones are met.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Applied Research</th>
<th>Development</th>
<th>Demonstration</th>
<th>Deployment</th>
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<tr>
<td>TRL</td>
<td>1 2 3</td>
<td>4 5 6</td>
<td>7 8 9</td>
<td>10</td>
</tr>
<tr>
<td>Scale</td>
<td>Bench</td>
<td>Pilot</td>
<td>Demonstration</td>
<td>Commercial</td>
</tr>
<tr>
<td>Stage Gate</td>
<td>Concept</td>
<td>Feasibility</td>
<td>Engineering</td>
<td>Finance</td>
</tr>
<tr>
<td>Institutions</td>
<td>Universities</td>
<td></td>
<td></td>
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<tr>
<td>National Laboratories / R&amp;D Organizations</td>
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<tr>
<td>Private Industry / Start-Up Companies</td>
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</tbody>
</table>
The research plan is detailed and granular.
Research Agenda Highlights
Uptake and Storage by Agricultural Soils

Primary Limitation:
Per-hectare rates of carbon uptake by agricultural soils

Research sponsors & performers:
- USDA, NSF, DOE
- Land-grant universities
- Natural Resource Conservation Service’s Conservation Innovation Grants

- $40-50M/y for development of new agricultural varieties that increase carbon removal and storage
  - Expand ARPA-E’s considerable investment in this area
- $11-14M/y for national agriculture soils monitoring system and experimental network improving agricultural soils processes
  - Extend carbon storage practices to cropping systems where previous work has been insufficient
  - Increase efficiency and reduce costs
Research Agenda Highlights
Afforestation/Reforestation and Forest Management

• Frontier research on preservation of harvest wood
  • if successful, could provide very large benefit at very low cost

• Basic research at $2.4 M/y for 3 years for landfill designs for achieving lowest possible rate of wood decomposition and integrated assessment of net greenhouse balance, costs, and required land, including the implications for worldwide consumption of wood products and their lifecycle emissions

• $3 M/y for 3 years for demonstration projects to improve the collection and disposal of wood products after use and for preserving harvested wood in different environments

Research investment: Low

Research sponsors and performers:
• USFS has a central role in furthering research and funding
• in partnership with USDA, NSF, and EPA
Research Agenda Highlights
Afforestation/Reforestation
Forest Management
BECCS

$3.7-14M/y for 10 years for **IAMs to improve humanity’s understanding of land-area constraint** facing these NETs

- Estimate how much land use change will occur elsewhere in world in response to
  - diversion of land to afforestation/reforestation
  - BECCS dedicated energy crops
  - reduced wood harvest
- Might allow increased carbon removal and if not, might reduce probability of making grave policy error
- Investment is not larger because committee believes that genuine understanding in this area is likely to improve only slowly.

**Primary Limitation:** Competition with food and biodiversity for land

**Research sponsors & performers:**
- Coordinated, cross-agency effort at USDA, DOE, EPA
- Research conducted by academic researchers and national laboratories
  - National laboratories should develop and curate publicly-accessible IAM platforms that can be leveraged by academic researchers
  - Coordinate international IAM efforts
Research Agenda Highlights
BECCS-to-Fuels with Biochar

$40-103 M/y for 10 years

- Research biochar permanence in soil and impact on crop productivity to determine its long-term value as a soil amendment and viability for carbon sequestration
- Develop conversion pathways that are both profitable from fuel production and carbon negative through co-production of large quantities of sequestered biochar

Primary Limitations:
- Uncertainty about biochar
- Challenging to achieve net negative GHG emissions

Research sponsors & performers:
- DOE, USDA, national labs → research and applied research
- Private industry, start-up companies lead → pilot and demonstration scale development
- National labs → operate pilot scale testing facilities
Primary Limitation: Cost is higher than economic demand

Research Agenda Highlights
Direct Air Capture

Research sponsors & performers:
- Cooperating and competing ecosystem of researchers, start-ups
- DOE Office of Fossil Energy, NETL → manage research, development, demonstration projects

Research Stages
1. Search for better materials and component designs with many $1 million efforts ($23-35M/y for 10 years)
2. Scale up new materials, components so they could be produced at scale necessary for pilot plant ($13-25M/y for 10 years)
3. Build and evaluate $20M/project pilot plants up to 1,000 tCO₂/y ($30-60M/y for 10 years)
4. Final scale-up to >10,000 tCO₂/y at $100M/project ($115-120M/y for 10 years)

National Direct Air Capture Test Center
- facilitate research
- conduct measurements of each entity’s technology using common basis for comparison
- disseminate public information while protecting intellectual property
Research Agenda Highlights

Carbon Mineralization

Primary Limitation:
Lack of fundamental understanding

Research sponsors & performers:
- DOE: Basic Energy Sciences Program and Office of Fossil Energy, combined with SubTER initiative
- NSF
- USGS
- University research

- Basic research on kinetics of carbon capture by minerals ($5.5M/y for 10 years)
- Basic research on rock mechanics, numerical modeling, and field studies to advance understanding of feedbacks between reaction and fluid flow for in situ applications ($17M/y for 10 years)
- Sequestration-only mitigation project: medium-scale injection of CO₂ into a basalt formation to provide alternative to saline aquifer storage ($10M/y for 10 years)

Credit: Lamont-Doherty Earth Observatory
Globally scaling up CO2 sequestration in deep geological formations is an enormous task:
- >100-fold scale-up from current sequestration operations
- Research needed to assess risks, select sites, and provide assurances that sequestration will be safe and effective
  - $50M/y reduce risks of *induced seismicity*
  - $45M/y increase efficiency and accuracy of *site characterization and selection*
  - $20M/y research ways to manage risk of *leakage of CO2 to atmosphere and groundwater*
  - $1M/y establish best practices for *community engagement, rules of practice, regulation guidelines*

Research sponsors & performers:
- DOE: research on trapping mechanisms; multi-scale, multi-physics modeling of fate and transport of CO2 in subsurface
- NSF: engage university research on Earth processes relevant to sequestration
- EPA: support development of reliable approaches regarding contamination sequestration sites
- USGS and BLM: further scale-up of geological sequestration
Rationale for Research Investment

• States, local governments, corporations, and countries now make or plan large investments in NETs (e.g. ~30% of planned emissions reductions).
  – Advances in NETs will create jobs and benefit US economy, especially if intellectual property is held by US companies.

• Unlike wind, solar and unconventional gas, NETs have not yet received public investment at a scale consistent with:
  – need for NETs that can solve substantial fraction of climate problem
  – possible magnitude of return to US economy
Thank you!

For more information and to subscribe for updates:
http://nas-sites.org/dels/studies/cdr/

Join the conversation on Twitter: #CarbonRemoval