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# Negative Emissions Technologies and Reliable Sequestration: A Research Agenda

## 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

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# Rationales for development and deployment of NETs

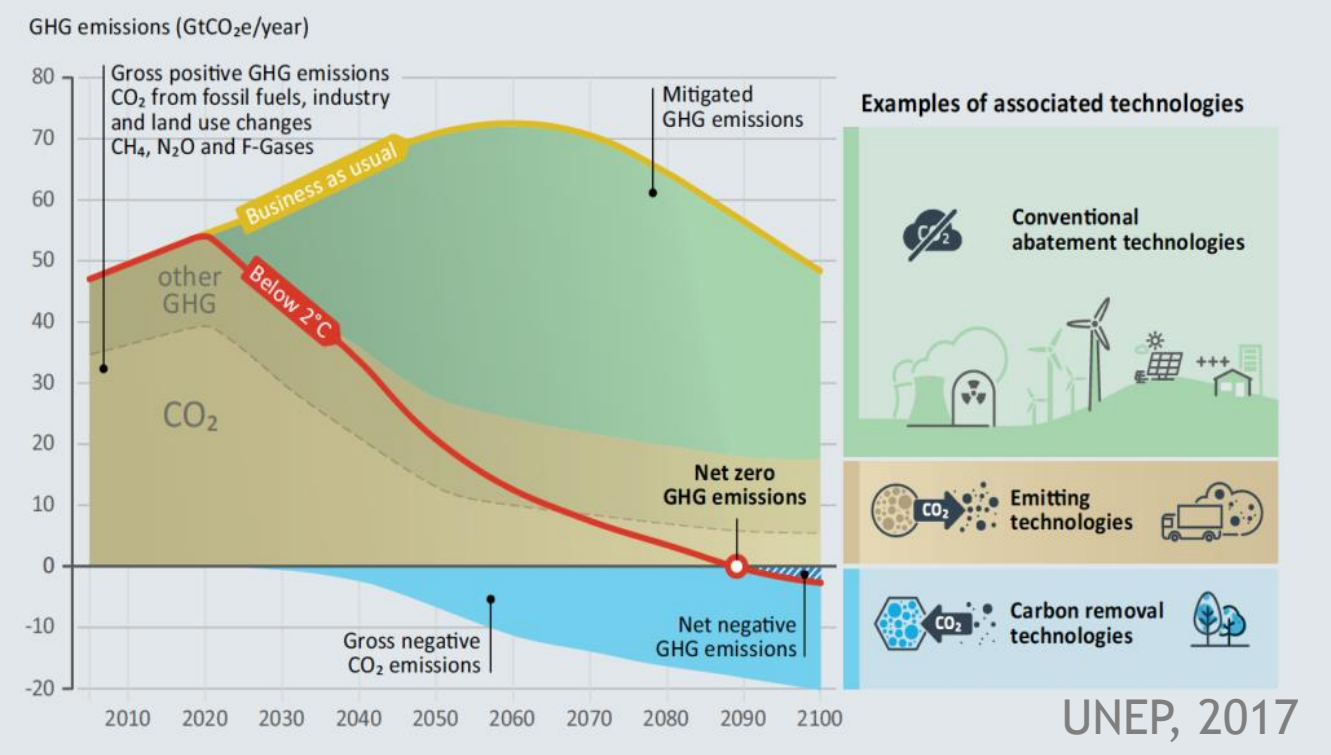
1. Reduce carbon pollution (i.e. 45Q tax credit in FUTURE Act)

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?




**~10 $GtCO_2$/y** globally by midcentury

**~20 $GtCO_2$/y** globally by the century's end

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# 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

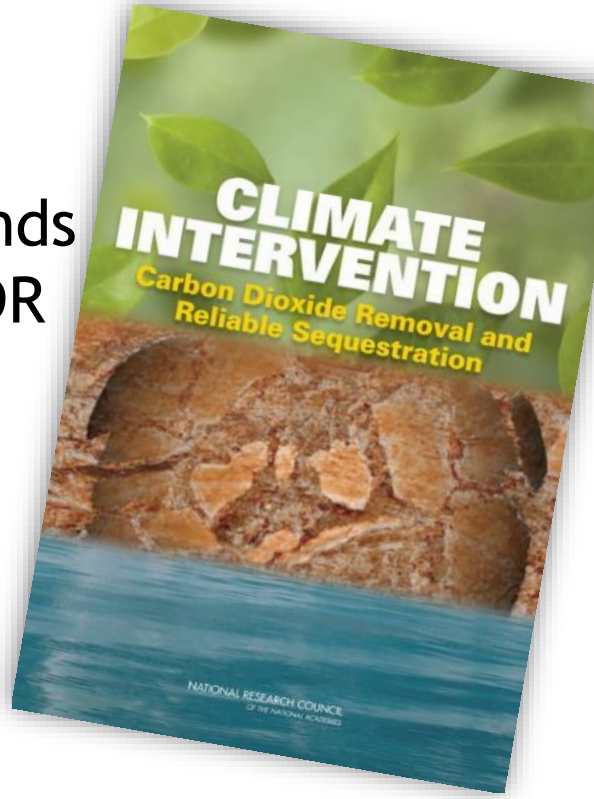


## For example…. Commercial Aviation

| | |
|---|---|
| Option 1: Develop Cellulosic Biofuels | Could be expensive and requires land to grow feedstock |
| Option 2: Capture and store 10 kg of atmospheric $CO_2$ with a NET for each gallon of fossil fuel consumed | If this cost \$50/t$CO_2$ then the offset would cost an additional \$0.50/gallon |

# 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

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- **Mark Barteau (NAE)**, Texas A&M University
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# Study Process

- Information gathering workshops
  - Coastal Blue Carbon Approaches (July 2017)
  - Land Management Practices (Sept. 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


Proceedings of a Workshop
IN BRIEF
May 2018
Direct Air Capture and Mineral Carbonation Approaches for Carbon Dioxide Removal and Reliable Sequestration
Proceedings of a Workshop—in Brief
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Proceedings of a Workshop
IN BRIEF
March 2018
Land Management Practices for Carbon Dioxide Removal and Reliable Sequestration
Proceedings of a Workshop—in Brief
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Proceedings of a Workshop
IN BRIEF
December 2017
Coastal Blue Carbon Approaches for Carbon Dioxide Removal and Reliable Sequestration
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July 2018
Bioenergy with Carbon Capture and Storage Approaches for Carbon Dioxide Removal and Reliable Sequestration
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Proceedings of a Workshop
IN BRIEF
September 2018
Geologic Capture and Sequestration of Carbon
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# Negative Emissions Technologies

Coastal blue carbon

Direct air capture

Terrestrial carbon removal and sequestration

Carbon mineralization

Bioenergy with carbon capture and sequestration (BECCS)

Geologic sequestration

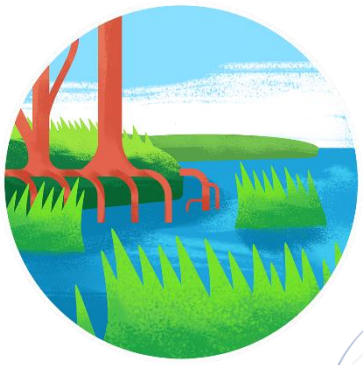
## Four NETs are ready for large-scale deployment:

- 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



| Negative Emissions Technology | Estimated Cost ($/tCO$_2$) L = 0-20 M =20-100 H = >100 | Upper Bound* for Safe* Potential Rate of CO$_2$ Removal Possible Given Current Technology and Understanding and at ≤$100/tCO$_2$ (GtCO$_2$/y) | |
|---|---|---|---|
| | | US | Global |
| Coastal blue carbon | L | 0.02 | 0.13 |
| Afforestation/ Reforestation | L | 0.15 | 1 |
| Forest management | L | 0.1 | 1.5 |
| Agricultural soils | L to M | 0.25 | 3 |
| BECCS | M | 0.5 | 3.5-5.2 |
| Direct air capture | H | 0 | 0 |
| Carbon mineralization | M to H | unknown | unknown |
| Total | | 1.02 | 9.13-10.83 |

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

*Safe means without without large-scale land-use change that could adversely affect food availability and biodiversity.

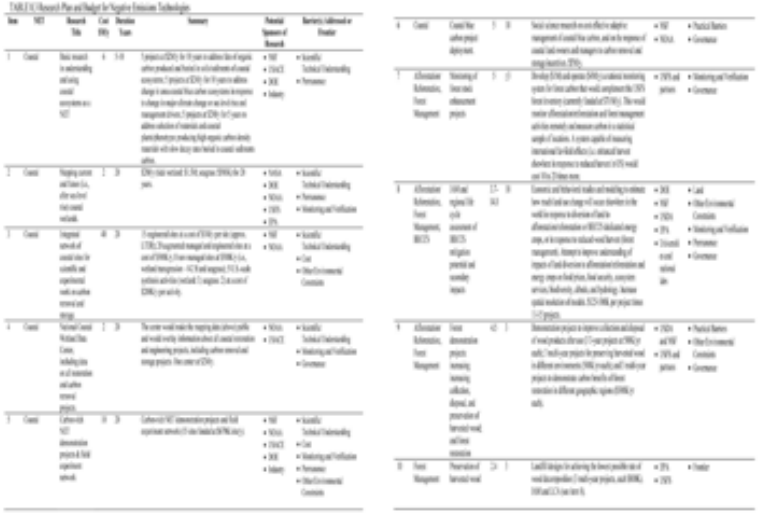
## Recommendation: The nation should launch a substantial research initiative to advance negative emissions technologies as soon as practicable:

(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

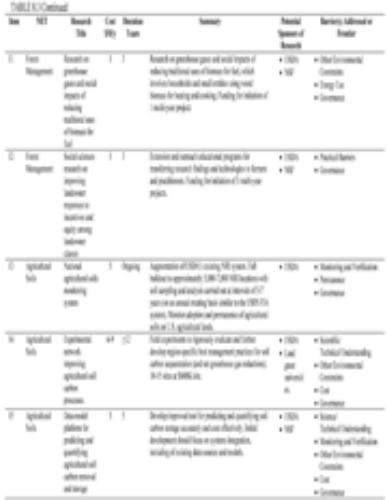
(2) make rapid progress on direct air capture and carbon mineralization technologies, which are underexplored but would have essentially unlimited capacity if high costs and many unknowns could be overcome

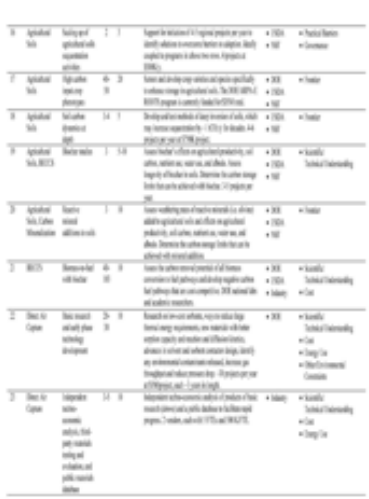
(3) advance NET-enabling research on biofuels and carbon sequestration that should be undertaken anyway as part of an emissions mitigation research portfolio

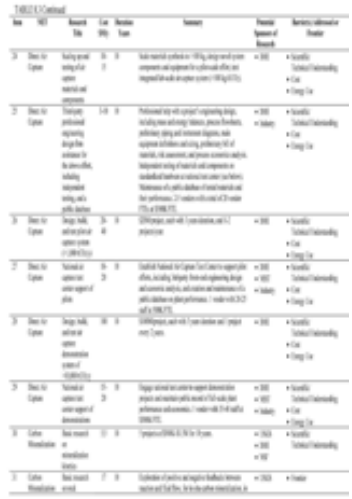
# NET Research

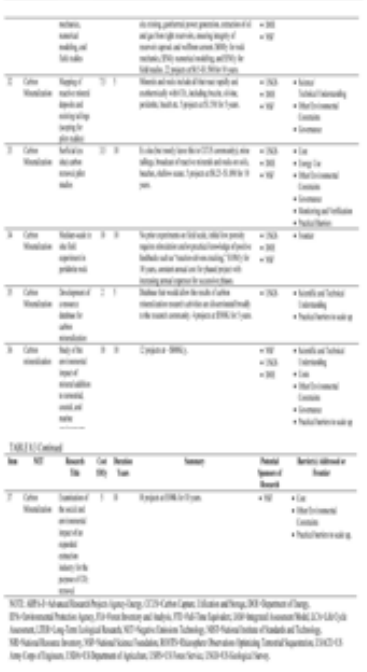




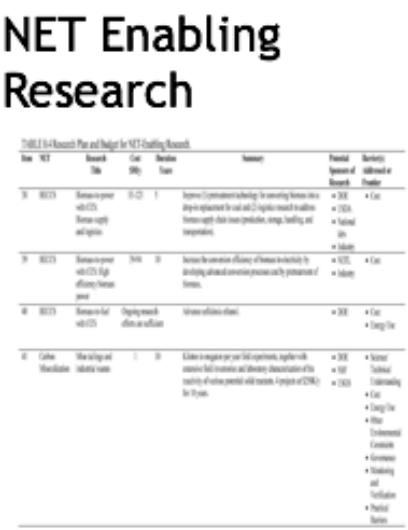


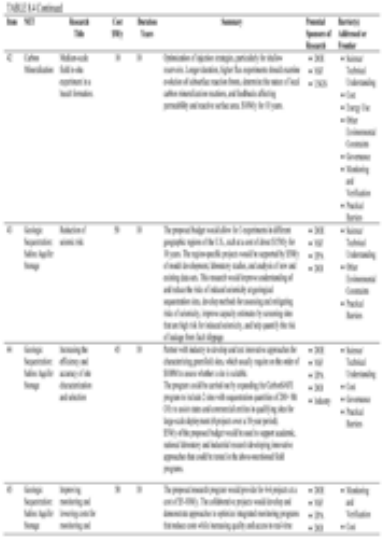


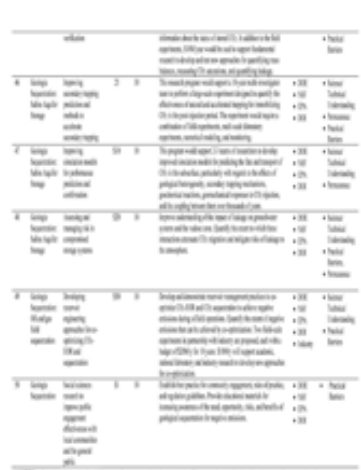




# NET Enabling Research





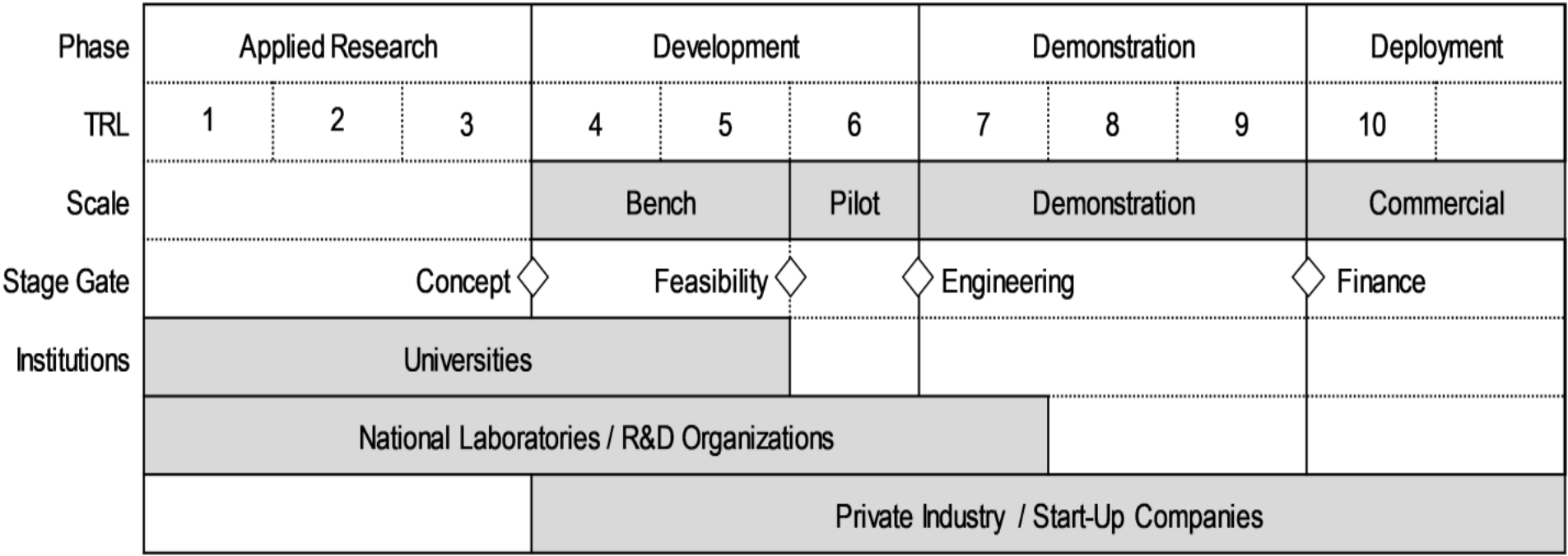


**The research plan is detailed and granular.**

# 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



# Research Agenda Highlights

## Coastal Blue Carbon

**Core of Research Plan:**

- Establish and operate network of research sites ($40M/y for 20 years)
  - Would straddle edaphic gradients and include both natural systems and those undergoing coastal engineering projects
  - Common set of measurements across network
  - How best to add CO2 removal and storage to coastal engineering projects at lowest cost

**Other Elements of Research Plan:**

- Basic research ($6M/y for 5-10 years)
- Map and monitor coastal wetlands ($2M/y for 20 years)
- Data center ($2M/y for 20 years)
- Social science research ($5M/y for 10 years)
  - cost-effective adaptive management
  - response of coastal land owners/managers to incentives
  - policies to manage responsibility for carbon lost to inundation/erosion

**Primary Limiting Factors:**

- Available land given coastal development and land use
- Understanding of future rates with sea level rise and coastal management

**Potential federal sponsors**

- NSF
- DOE
- EPA
- NASA
- U.S. Army Corps of Engineers
- NOAA

# Research Agenda Highlights

## Afforestation/Reforestation and Forest Management

- Frontier research on preservation of harvest wood
  - 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 collection and disposal of wood products** after use and for **preserving harvested wood** in different environments

**Research sponsors and performers:**

- USFS has a central role in furthering research and funding
- in partnership with USDA, NSF, and EPA

# 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 20 years 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

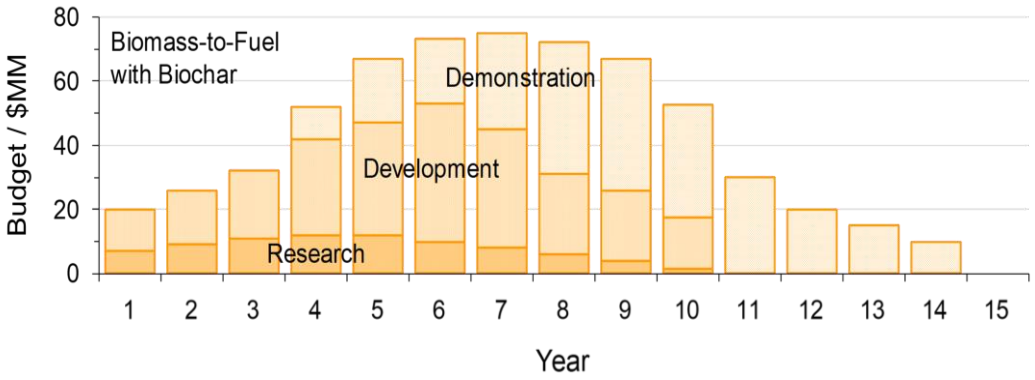
## BECCS-to-Fuels with Biochar

**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

### $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

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# 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 slowly.

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

**Research sponsors & performers:**

- Coordinated, cross-agency effort at USDA, DOE, EPA
- Academic researchers and national laboratories
  - Develop and curate publicly-accessible IAM platforms
  - Coordinate international IAM efforts

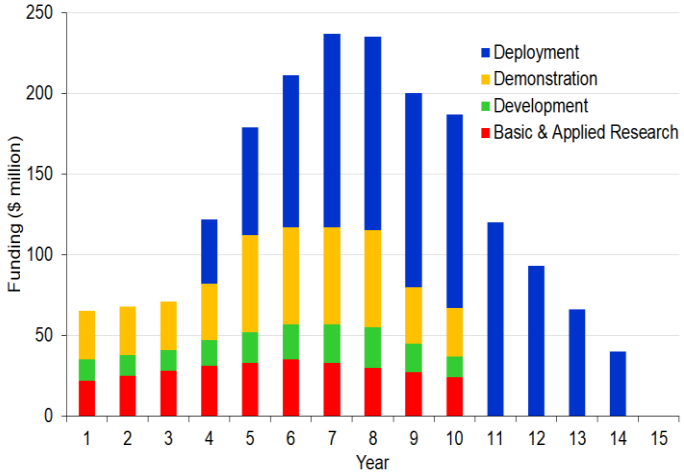
# Research Agenda Highlights

## Direct Air Capture

**Primary Limitation:**
Cost is higher than economic demand

**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 $tCO_2$/y ($30-60M/y for 10 years)
4. **Final scale-up** to >10,000 $tCO_2$/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

Credit: Lamont-Doherty Earth Observatory

- 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 $CO_2$ into a basalt formation** to provide alternative to saline aquifer storage ($10M/y for 10 years)

# Research Agenda Highlights
## Geologic Storage of Carbon Dioxide

**Primary Limitation:**
Practical barriers to scale up

- Globally scaling up CO2 sequestration in deep geological formations is enormous task:
  - >100-fold scale-up from current sequestration operations
- Research needed to assess risks, select sites, 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

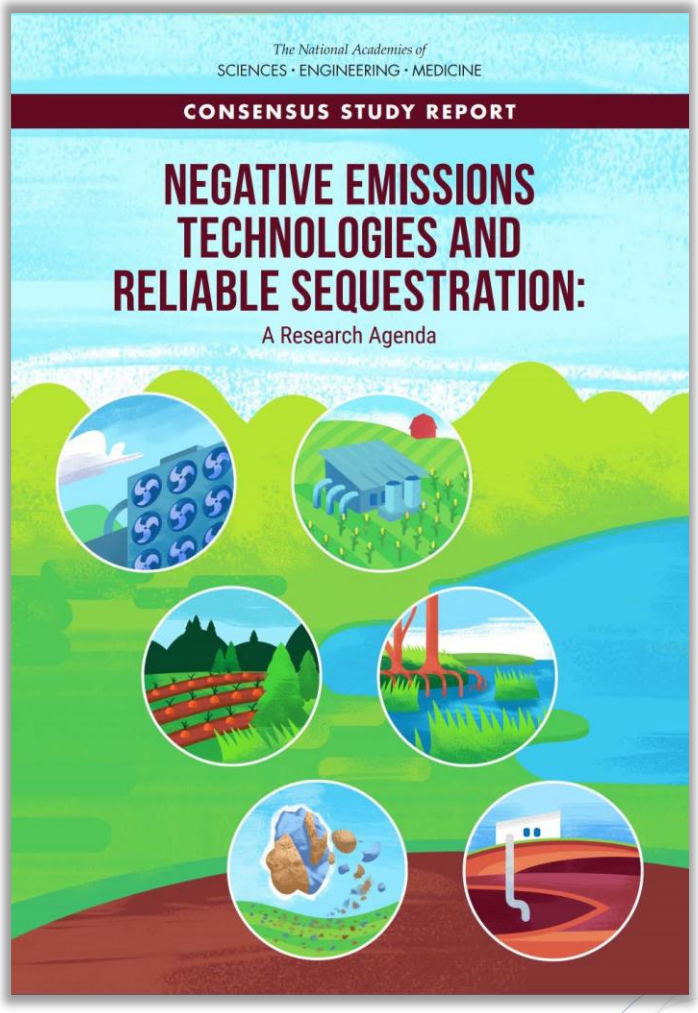
- States, local governments, corporations, and countries now make or plan large investments in NETs (e.g. ~30% of planned emissions reductions).
  - Advances in NETs will create jobs and benefit US economy, especially if intellectual property is held by US companies.
- Unlike wind, solar and unconventional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



- Extra slides

# Highlights of Research Agenda

- Large "staged" investments to
  - advance high-capacity NETs (direct air capture & carbon mineralization)
  - understand and perhaps soften land constraint facing afforestation/reforestation, forest management, agricultural soils, BECCS
- Many research efforts should be funded by federal agencies, but some would benefit from public-private partnerships
  - e.g., National Air Capture Test Center to support pilot efforts
- Most research topics chosen to pay off within ~10 years
- Some "frontier" research may not pay off fully for ~20 years or more
  - Plant breeding
  - Enhanced weathering in situ in ultramafic rock

# Carbon dioxide removal can be part of a carbon capture, utilization and sequestration system


Carbon waste gases are captured at its point of production or from the atmosphere and may be separated from other byproducts, compressed and/or transported.

**Sequestered**: Captured carbon may be disposed of thousands of feet underground where it can remain permanently trapped

**Utilized:** $CO_2$, $CH_4$ and biogas may be used as a feedstock for products that have market value, such as fuels, building materials, plastics or other useful solids, chemicals or animal feed. (see also sister study: *Gaseous Carbon Waste Streams Utilization: Status and Research Needs*, http://nas-sites.org/dels/studies/gcwu/).

# Terrestrial carbon removal and sequestration

- Afforestation/reforestation
- Changes in forest management
- Changes in agricultural practices that enhance soil carbon storage
- Limiting factors:
  - Available land
  - Practical barriers
  - Demand for wood
  - Limited per-hectare rates of carbon uptake

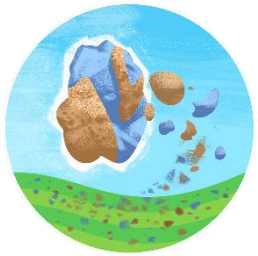
# Bioenergy with carbon capture and sequestration (BECCS)

- Plant biomass used to produce electricity, liquid fuels, heat
- Combined with capture and sequestration of $CO_2$ produced when using bioenergy and any remaining biomass carbon that is not in liquid fuels
- Limiting factors:
  - Cost
  - Availability of biomass
  - Inability to fully capture waste biomass
  - Fundamental understanding

# Direct air capture

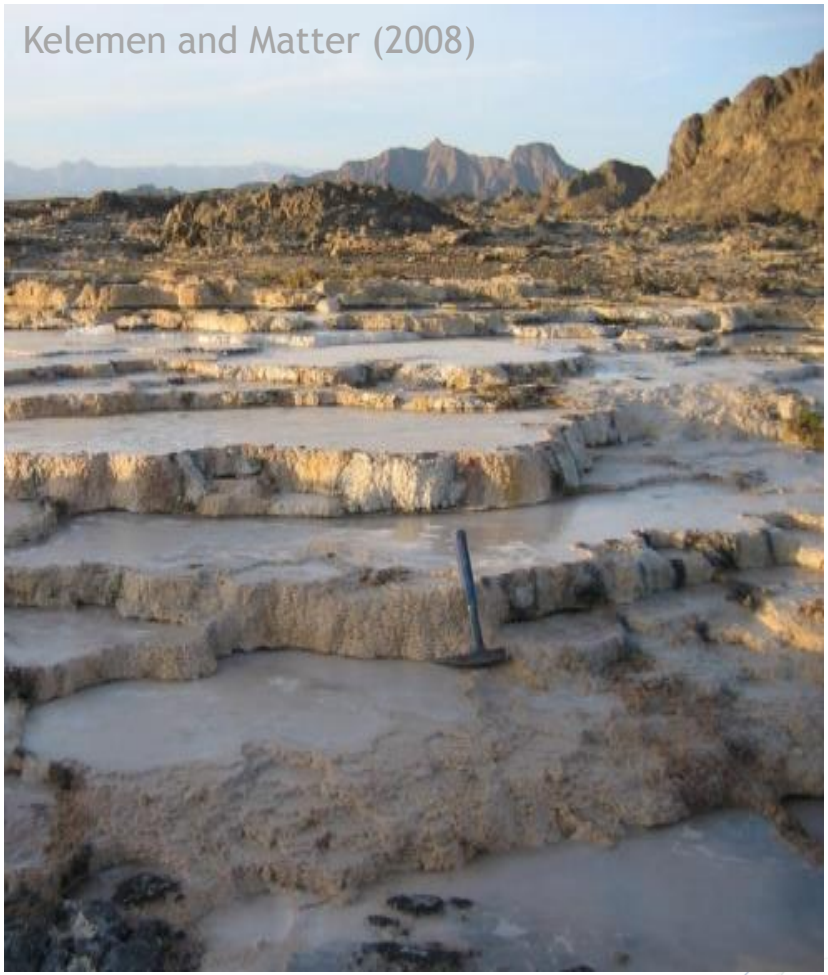
- Chemical processes that capture $CO_2$ from ambient air and concentrate it
- The captured $CO_2$ can be injected into a storage reservoir
- Limiting factors:
  - Cost greater than economic demand
  - Practical barriers to pace of scale up

Credit: Climeworks



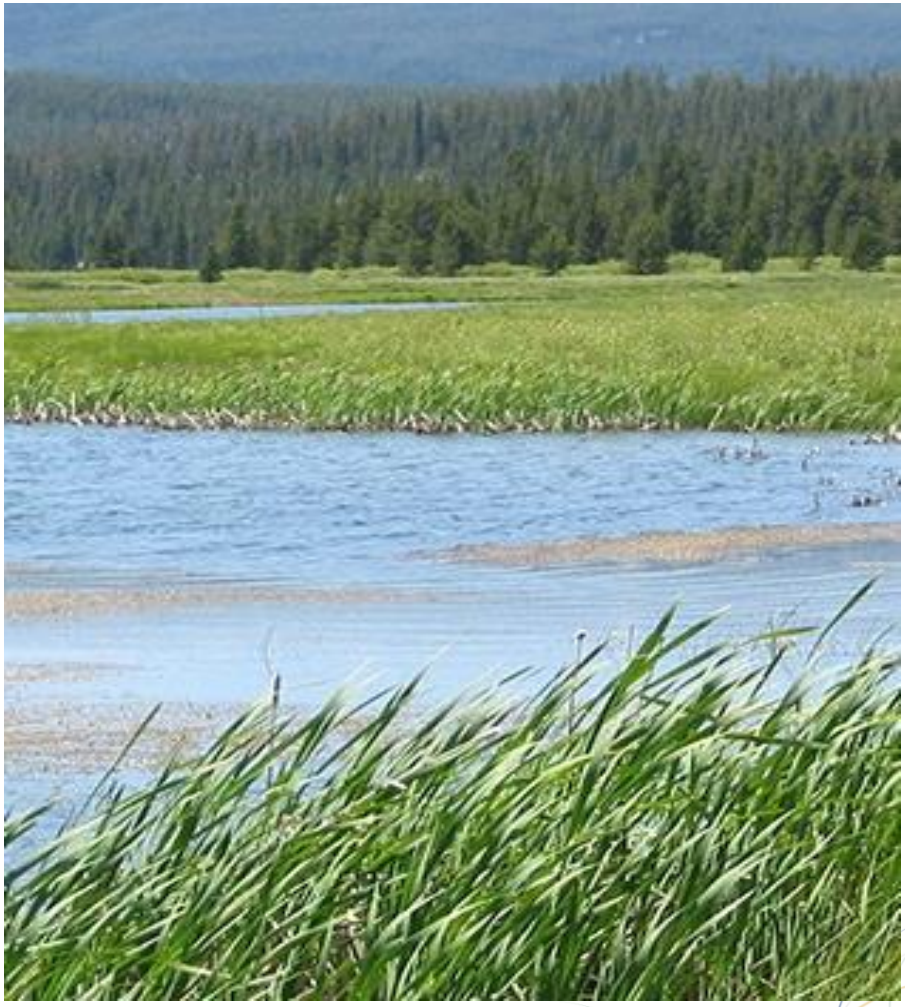
# Carbon mineralization

- Accelerated “weathering”
- Atmospheric $CO_2$ forms a chemical bond with reactive minerals
  - Ex Situ: Occurs at surface where $CO_2$ in ambient air is mineralized on exposed rock
  - In Situ: Occurs in subsurface where concentrated $CO_2$ streams are injected into ultramafic and basaltic rocks where it mineralizes in pores
- Primarily limited by lack in fundamental understanding



# Coastal Blue Carbon

- Practices that increase amount of carbon stored in living plants or sediments in tidal marshlands, seagrass beds, and other tidal or salt-water wetlands
- Limiting factors:
  - Available land given coastal development and land use
  - Understanding of future rates with sea level rise and coastal management



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# Geologic sequestration

- $CO_2$ captured through BECCS or direct air capture is injected into a geologic formation where it remains in rock pore space for a long time
- Not a NET, rather an option for sequestration component of BECCS or direct air capture
- Practical limits will be set by availability of $CO_2$, pipelines, regulatory infrastructure and public opinion