Breakout 1 – Individual Pathways

BREAKOUT A – FEEDSTOCK PATHWAYS

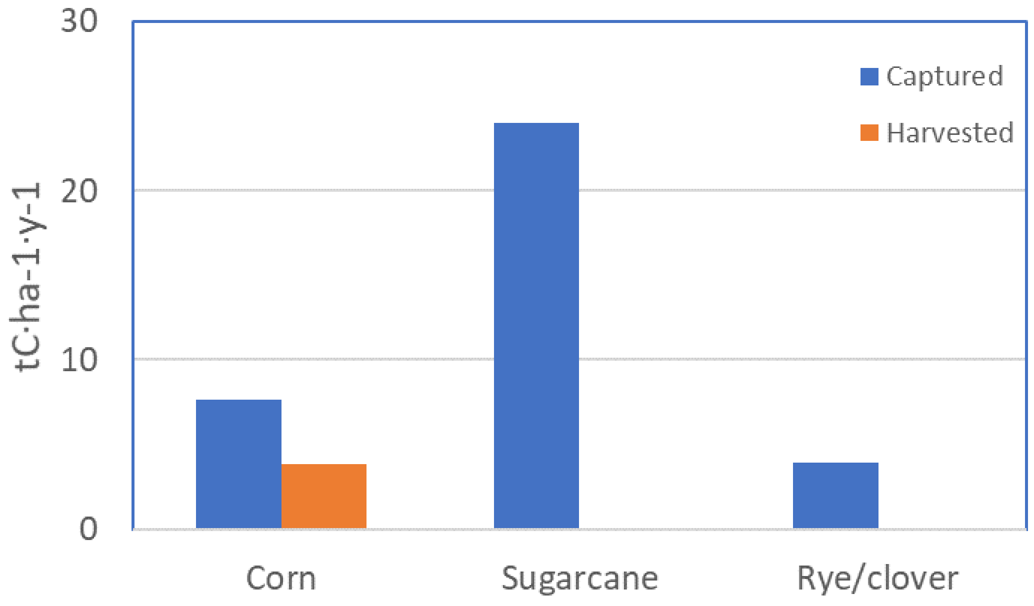
Feedstock pathways of interest

- **Parallel pathways:** modify today's fuel/food/fiber crops to increase their carbon removal potential
  - e.g., deeper roots, increased carbon in residues
- **Exclusive pathways:** design crops for the sole purpose of carbon removal
  - e.g., fast growing, water/nutrient efficient
- **Cover crops:** rewire the cover crop to overcome adoption barriers, improve soil health, and remove carbon
  - e.g., winter hardiness, low/no input requirements, nutrient fixing

Feedstock Potential

Various crop feedstocks have different intrinsic carbon yields which can be determined from harvested biomass and composition.

- Parallel (Corn)
- Exclusive (Sugarcane as a proxy)
- Cover crop (Rye/clover mix)



Across the acreage planted in 2021, corn captured 290 Mtons and cover crops* 19 Mtons of carbon.

What technical metrics for success should we focus on?

arpa·e CHANGING WHAT'S POSSIBLE

Poll

Which crops /plants should we focus on for parallel* pathways?

- Biofuel
- Fiber
- Food – commodity
- Food – specialty
- Forestry
- Rangeland

*Modify today's fuel/food/fiber crops to increase carbon removal

Follow-up questions

- What makes the top-selected crop types most suitable for parallel pathways?
- Should technology developments for these pathways prioritize emissions avoidance, or removal?
- What are some examples of high-risk/high-impact developments related to increasing the carbon drawdown potential of these pathways?

Feedstock pathways of interest for parallel approaches

- What conflicts, if any, exist between improvements in belowground and aboveground biomass carbon removal? Does pushing carbon into rhizosphere necessarily reduce aboveground carbon?

- **Aboveground**: How much biomass can you sustainably harvest to utilize for BiCRS systems? How much needs to be left in the field to retain organic matter?
  - How do you engineer biomass to ensure residue is of the greatest benefit for carbon stability and ecosystem health? e.g., can you design the biomass residue to be more recalcitrant?

- **Belowground**: What are the realistic approaches for increasing the root depth profile?
  - What are some of the promising genes/traits involved in that?

BiCRS = Biomass Carbon Removal and Storage

Feedstock pathways of interest – Parallel*

- **Avoidance**: What are the potential synergies between carbon removal and emissions avoidance pathways? What are the potential trade-offs?

- **Adaptability:** What are the potential synergies between designing for carbon removal and designing for climate resilience/adaptability? e.g., water use efficiency, heat tolerance, elevated CO_2 levels
  - With expected change in climates/growing ranges, should ARPA-E emphasize improving adaptability such that existing crops can be grown “anywhere,” or focus on optimization for current growing environments knowing crops will ultimately need to move geographies?

*Modify today’s fuel/food/fiber crops to increase carbon removal

Poll

Which land types should we focus on for exclusive* pathways?

- Cropland
- Rangeland
- Forests
- Grassland
- Marginal land
- Other: Turf, O&G fields, brownfields

*Design crops for the sole purpose of carbon removal

Follow-up questions

- What makes the top-selected land uses most suitable for exclusive pathways?
- What are some examples of high-risk/high-impact developments related to increasing the carbon drawdown potential of these land uses?
- For land uses with low/no votes, should we consider them out of scope/not of interest?

Feedstock pathways of interest – Exclusive*

- **For the priority land types,** which plants/crops should we prioritize to:
  - Serve as baseline(s)
  - Engineer for enhanced carbon removal

- **Aboveground vs belowground** – Which has more potential, belowground (i.e. roots) vs. aboveground carbon fixation? Which do you feel is most realistic to deploy in a 3-to-4-year timeframe?

- Given priority plants/crops and the potential for above/belowground improvements, what are the most promising innovation pathways? How would those pathways be evaluated in a field environment?

*Design crops for the sole purpose of carbon removal

Feedstock pathways of interest – Exclusive*

- **System design** – Are there agronomic practices or equipment that need to be developed/optimized to deploy dedicated carbon crops? Why is the carbon stock often higher in wild/native prairie habitats, and what can we do to promote those synergistic effects in managed lands?

- **Net carbon optimization** - How can we co-optimize for carbon removal *and* emissions avoidance? e.g., fast growing, low input requirements

*Design crops for the sole purpose of carbon removal

Feedstock pathways of interest – Cover crops

- What are the primary drivers for cover crop adoption?

- What is holding back more widespread adoption? Are there technical developments that, if successful, would help drive adoption?
  - Economic challenges
  - Operational challenges
  - Feedstock challenges

Poll

Which properties should be prioritized for the design of an ideal cover crop?

- Nutrient fixation
- Nutrient efficiency
- Soil stability/erosion protection
- Water efficiency
- Carbon content
- Deep roots
- Pest/disease prevention
- Seasonal hardiness

Follow-up questions

- For the priority traits identified, do we have the tools and understanding we need to select for them?
- What synergies/tradeoffs exist between potential cover crop priorities?

Feedstock pathways of interest – Cover crops

- How do you define what the most promising cover crops/feedstocks are?
  - By geographic coverage?
  - By planting window?

- Do cover crops offer unique carbon farming pathways not available to food/fuel/etc. crops?

- What are the best uses for cover crop biomass?

BREAKOUT B – MICROBIAL PATHWAYS

CHANGING WHAT'S POSSIBLE

Microbial pathways of interest

- **Leveraging the biological processes of microorganisms that contribute and/or control storage of carbon in the soil and control emissions in the field.**

- **Conversion:**
  - Contribution to soil organic matter
    - Plant biomass
    - Necromass production

- **Durability:**
  - Long-term stabilization:
    - soil aggregates
    - soil organic compounds

- **Emission Avoidance:**
  - Reducing respiration
  - Conversion of CH_4 and N_2O from field

Potential for microorganisms: Avoidance, Removal, or Both?

- What has the greatest potential – leveraging microorganisms for emissions avoidance or carbon removal?
  - What is the technical/theoretical potential?
  - What is the real-world potential?
  - If N_2O emissions can be avoided using N-fixing microorganisms, should the respiration (CO_2) rate be deducted from emissions savings?

Poll

If microbes could be engineered or selected for their ability to increase soil carbon, which pathways would be most promising to focus research efforts?

- Decomposition of plant matter to Soil organic matter
- Production of microbial necromass
- Altering microbial carbon use efficiency (reduce respiration)
- Stabilization of soil aggregates
- Other pathway not listed

Follow-up questions

- Why would the top selection result in achieving a moonshot target?
- What would you specifically engineer for in that pathway?
- What carbon compounds should be focused on?
- What are the challenges and opportunities of developing the selected pathway?

Microbial pathways of interest – Conversion

- What is the potential for microbial carbon sequestration when
  - Applied to agricultural lands compared to native habitats?
  - Using wild-type strains compared to genetically engineered microorganisms
- Should a microbial solution for carbon sequestration focus on conversion or stabilization?
- If you could fund specific projects that could yield a soil microorganism that increases sequestered carbon, what would that be?
  - What are the specific challenges to be overcome as part of an approach?
  - What could be accomplished in a 3-5 year timeframe, and what gaps/risks would remain?

Poll

Which of the following has the greatest influence on how the soil microbiome stabilizes biomass carbon?

- Soil organic matter
- Temperature
- pH
- Bulk density
- Soil composition
- Moisture
- Microbiome diversity
- Other property not listed

Follow-up questions

- How do the top 2-3 selections positively and/or negatively influence carbon stabilization?
- What opportunities exist to mitigate negative influences and/or leverage positive influences?
- What are the resulting carbon compounds? How do they mitigate the potential for leakage?

Microbial pathways of interest – Durability

- What are the methods by which carbon can be converted into a long-duration storage medium? What role does, or can, the microbiome play in this process?
- What genetic pathways could be exploited, or what compounds should a microorganism produce, to enhance long-term soil carbon content?
- What are the carbon-containing species that are possible, and would they pass through a biological or engineered conversion pathway, or both?

Poll

What are the most promising pathways for microbe-based emissions avoidance?

- Reduced N_2O emissions via Nitrogen fixation
- Inhibit N_2O
- Inhibit CO_2
- Inhibit CH_4

Follow-up questions

- For the highest-ranked pathway, what technical developments/achievements have the greatest impact potential?

- Where/how do these achievements overlap with private-sector pursuits? Are there areas that are too risky for the private sector that could be more appropriate for an ARPA-E program?

Microbial pathways of interest – Avoidance

- Are we missing opportunities by focusing only on the soil microbiome? Are there other microbes/microbial systems that would enable rapid/dense carbon removal?
  - e.g., develop CH_4-eating microbes to distribute in rangelands

BREAKOUT C – ENGINEERED PATHWAYS

Breakout Topics:

- **Engineered solutions for carbon farming:** enhanced weathering (EW) & biochar
  - What is the potential?
  - What is the technical potential?
  - Where/how can ARPA-E funding make a difference?

- **Conversion/Stabilization**
  - Which supply chain pathways should ARPA-E prioritize?
    - Potential for scale
    - Potential for impact

Engineered pathways of interest – Enhanced Weathering (EW)

- What's holding EW back from widespread adoption?
- What are the agricultural, environmental, or economic risks (real or perceived) associated with the deployment of this pathway? What are the benefits?
- Do we have the predictive tools we need to evaluate EW approaches?

Engineered pathways of interest – Enhanced Weathering (EW)

- What are the best ways to apply pulverized rock to enhance CDR?
- Are certain land types more/less amenable to EW?
- What are the potential synergies with plant-and microbe-based approaches?
- What fraction of C captured by EW partitions into:
  - Carbonate minerals that stay on land
  - Carbonate minerals to runoff
  - Soil and/or biomass

Poll

- Rank the following challenges for biochar by their potential for a technology fix:
  - Yield per unit biomass input
  - Production cost
  - Logistics
  - Impact on soil microbes
  - Recalcitrance
  - Other

Follow-up questions

- Any surprises, or general feedback, on the responses here? (anyone that chose "Other property not listed" willing to share what we're missing?)
- What about the top selected challenge makes it suitable for a technology fix?
- Are there promising developments underway? Is there additional technology "white space" to be addressed by a potential ARPA-E program?

Engineered pathways of interest – Biochar

- What's holding biochar back from widespread adoption?
- What are the agricultural, environmental, or economic risks (real or perceived) associated with the deployment of this pathway? What are the benefits?
- Are there certain land use types that would be more/less amenable to this approach?
- How would the carbon storage impact be measured?
- How would a carbon payment most likely be allocated across a biochar supply chain?

Engineered pathways of interest – Conversion/Stabilization

- What are the methods by which atmospheric carbon can be converted into a long-duration storage medium?
- What are the logistical challenges associated with widespread BiCRS pathways? Which present the greatest threat to scaling these pathways?
- What kinds of offtake/supply guarantees need to be in place in order to establish/scale downstream conversion/stabilization pathways?
- What do these agreements need to look like in order to secure steady supplies (i.e., what are the requirements and benefits for the grower)?

BREAKOUT D – AVOIDANCE PATHWAYS

Example avoidance pathways

- **Assumptions:** *Zero production emissions for farm inputs (fertilizer, herbicide, pesticide); zero-carbon global electrification; supply chain capabilities*

- **N_2O:** e.g. inhibition amendments; microbe treatments; bioreactors
  - *Not: …variations between source material, incrementing decision-support or prescriptive tools*

- **CO_2:** e.g. bioreactors; engineered traits
  - *Not: …equipment/energy emissions, established practice changes*

- **CH_4:** e.g., …natural fertilizer innovations; wetland buffer management
  - *Not: … enteric fermentation, food waste*

Poll

- What are the most promising pathways for reducing ag-related N_2O emissions?
  - Microbial N fixation
  - Crop N efficiency
  - N inhibitors
  - Precision nutrient management
  - Precision water management
  - “Green” fertilizers
  - Other

Avoidance pathways of interest – N_2O

- For the top 3 pathways selected, what are the most promising innovation pathways?
  - Which have the greatest technical potential?
  - Which have the greatest potential for commercialization/scale?
  - What can reasonably be achieved in a 3-to-5-year timeframe?
  - How would those pathways be evaluated in a field environment?
- How do we set a baseline for N_2O emissions? What is our best current understanding of the status quo?
- What processes should be of highest importance for monitoring?
- What gaps in our understanding/toolkit exist?
- Which are most difficult to address currently? Why?

Avoidance pathways of interest – CO_2 and CH_4

- In a model carbon farming operation (100% zero carbon on-farm energy, all inputs have zero carbon footprint, etc.), which sources of CH_4 and CO_2 emissions will still occur at the field?
- What is our best current understanding of the status quo in terms of these emissions?
- What processes should be of highest importance for monitoring?
- Opportunities for abatement?
- What gaps in our understanding/toolkit exist?
- Which are most difficult to address currently? Why?
- What technologies would best address those emissions sources?
  - New crop varieties
  - Microbial applications
  - Abiotic soil amendments
  - New management practices
- Which should we be focusing on? Which are the most in need of a technology fix?