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Open scientific questions on carbon removal

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Three cross-cutting challenges

01 — The universe of potential carbon removal approaches is expanding; approaches that may have a large role in national net zero strategies are nascent.

02 — For many carbon removal approaches, the specifics of deployment have a strong influence on the actual carbon removed.

03 — The actual carbon removal can be separated from a project activity in both space and time, creating challenges around reporting when and where removals occur.

Examples

For several carbon removal approaches, I'll describe the key uncertainties, as well as the inventory sectors where the following parts of the carbon removal process take place:

- **Sink** — the activity that leads to carbon removal
- **Removal** — the process of actual atmsospheric carbon removal
- **Storage** — the storage activity and ultimate storage reservoir

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CDR Verification Framework

This is an interactive tool for understanding Verification Confidence Levels (VCLs) for carbon dioxide removal (CDR) by mapping key uncertainties for different CDR pathways. Developed in collaboration between CarbonPlan and Frontier. Read the explainer article, the Frontier post, or methods for more detail.

ALL DRAWDOWN EMISSIONS DURABILITY

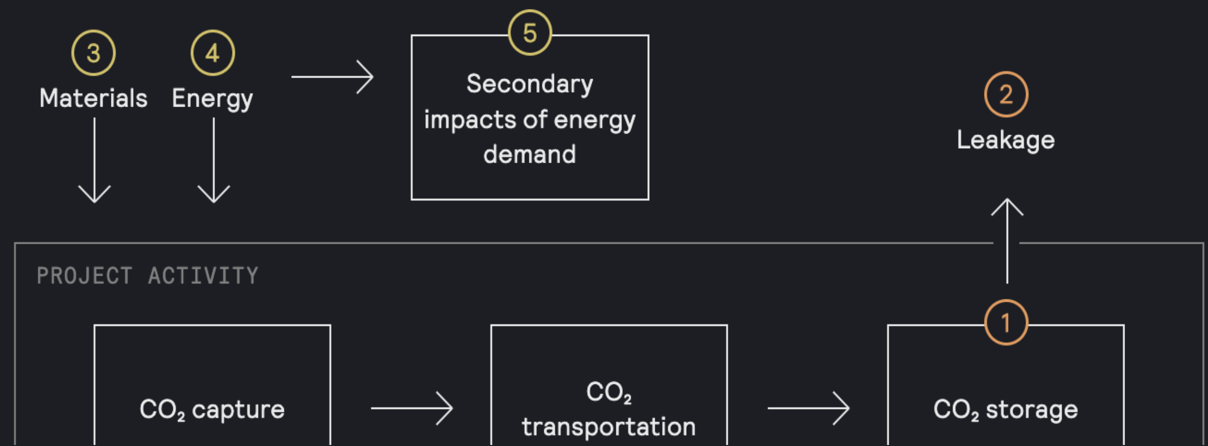
Component	Uncertainty
(1) CO_2 storage	
(2) Leakage	
(3) Materials	

Direct Air Capture v1.0 VCL 4-5

Direct air capture (DAC) uses chemicals to capture CO_2 from ambient air and generate a concentrated stream of CO_2 for storage. We assume that captured CO_2 is not used for enhanced oil recovery. This pathway is VCL 4-5, meaning that current quantification capacity can establish permanent carbon removal with relative confidence. View pathway documentation.

TOTAL CARBON REMOVAL $_{CO_2e}$ = DRAWDOWN $_{CO_2e}$ - EMISSIONS $_{CO_2e}$

= ((1) - (2)) - ((3) + (4) + (5))



CDR Verification Framework

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CDR COMPANIES	Arca, Captura, Carba, Charm, Climate Robotics, Ebb, Eion, Heirloom, Kodama, Planetary, Rewind, Running Tide, SeaO2, Takachar, Travertine, UNDO (prev. Future Forest), Vaulted
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Land-based enhanced weathering

Speeding up the chemical reactions between rocks, water, and air to remove CO_2 from the atmosphere.

SECTORS

- **Sink** activity primarily in croplands
- **Removal** in croplands, terrestrial waters, and/or oceans
- **Storage** primarily as dissolved inorganic carbon in terrestrial waters and oceans

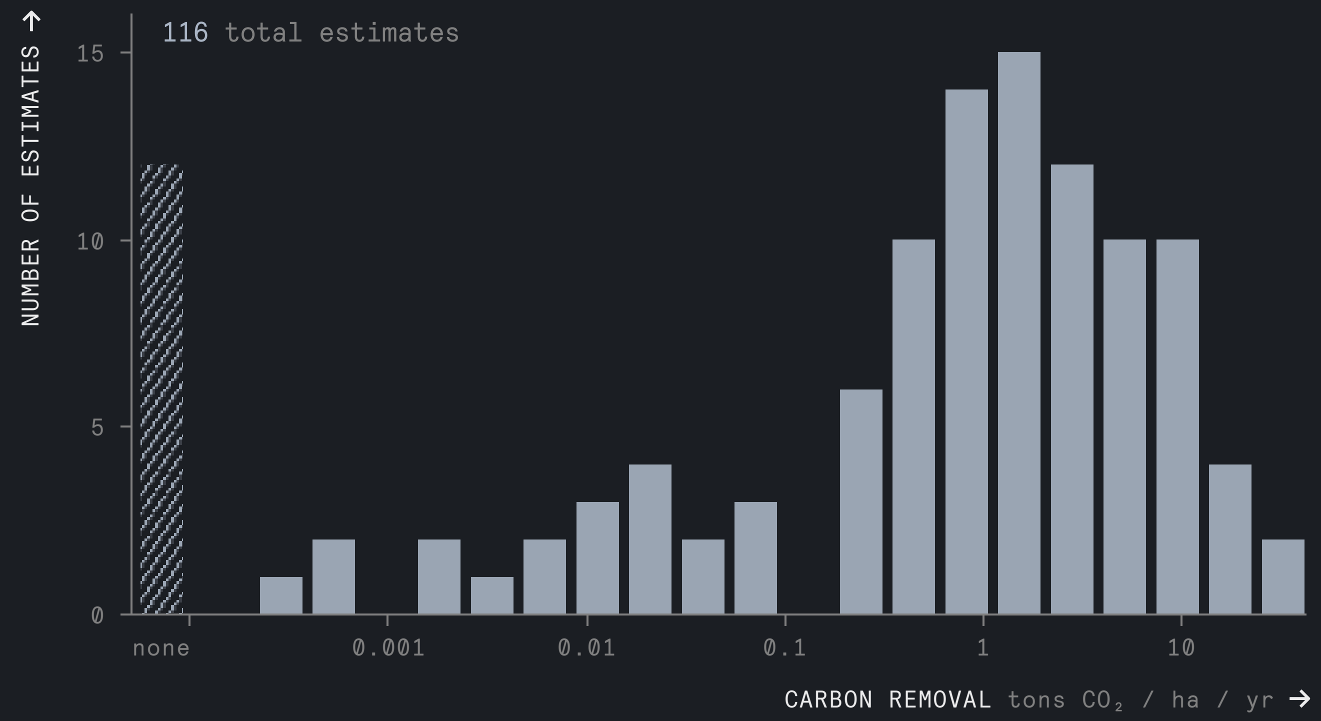
KEY UNCERTAINTIES

- Rock weathering rates
- Carbonate precipitation and clay formation
- Strong acid neutralization
- Natural alkalinity cycle impacts
- Nonlinear losses that emerge with scale or climatological change
- Soil organic carbon impacts (captured in existing soil inventory)

Land-based enhanced weathering

Carbon removal flux estimates from enhanced weathering studies span more than four orders of magnitude.

Differences arise due to variation in operational decisions (e.g. rock type, grain size, application rate, location, quantification approach) and which downstream uncertainties are accounted for.



Ocean alkalinity enhancement

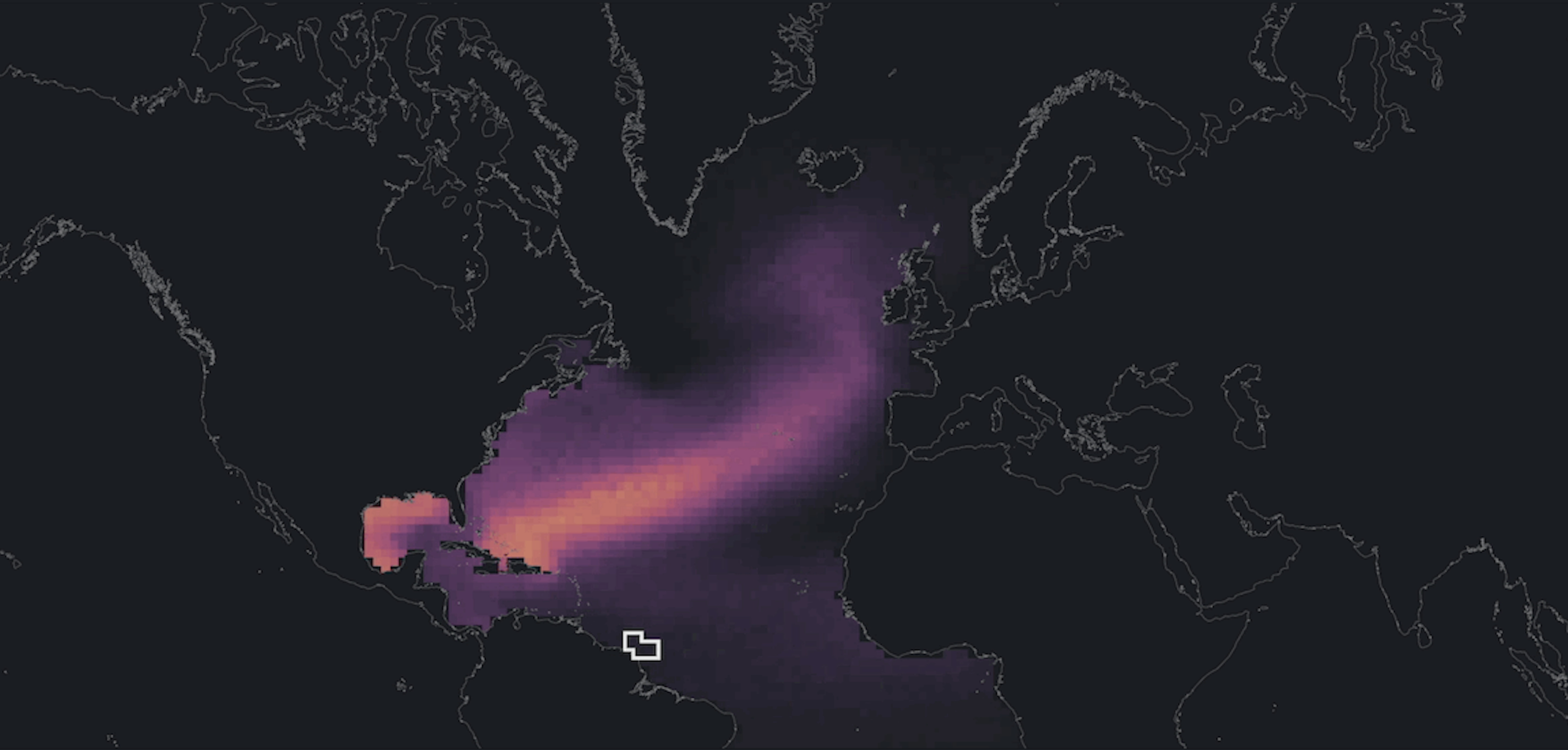
Adding alkalinity to the surface ocean to enhance its uptake and storage of atmospheric CO_2.

SECTORS

- **Sink** activity primarily in coastal waters
- **Removal** often occurring over large regions of the ocean
- **Storage** as dissolved inorganic carbon in the ocean

KEY UNCERTAINTIES

- Mineral dissolution (mineral-based only)
- Long-term fate of acid (electrochemical only)
- Carbonate precipitation
- Air-sea gas exchange
- Natural alkalinity cycle impacts
- Nonlinear losses emerging at scale

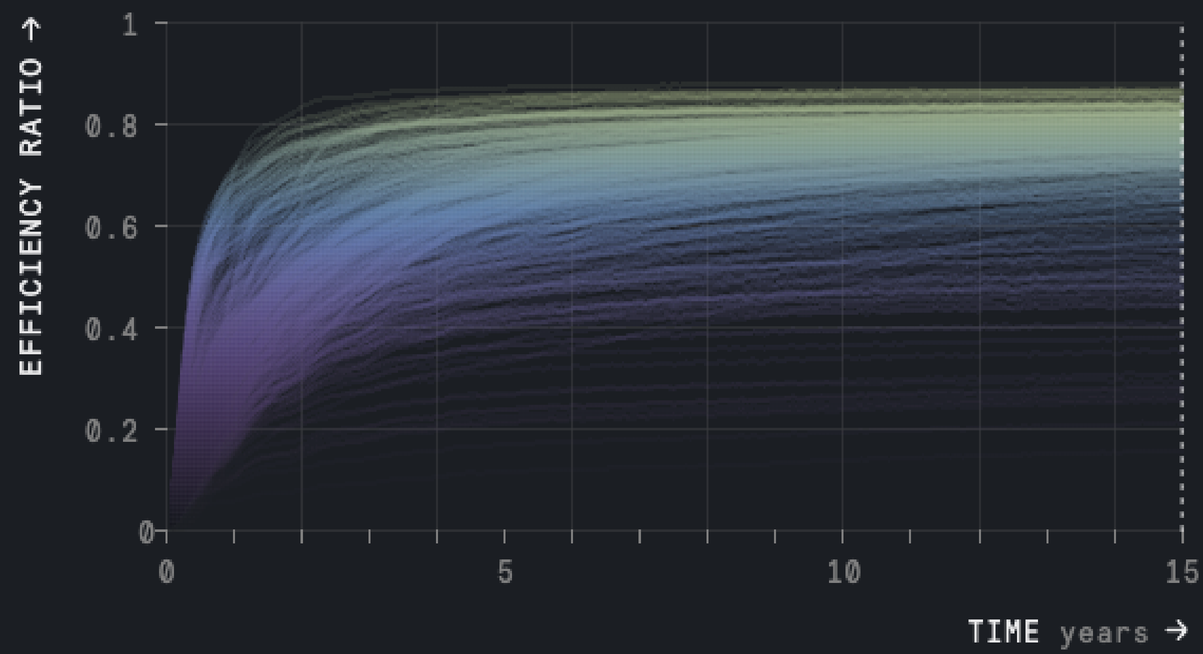


Ocean alkalinity enhancement

Adding alkalinity in different locations or seasons can lead to different carbon removal outcomes.

Early modeling indicates that in many regions, carbon removal approaches theoretical maximum within 15 years.

Removal can be cut short if alkalinity moves away from the surface ocean.



Biomaterial injection

Using photosynthesis to remove CO_2 from the atmosphere, transforming the resulting biomass (e.g. via pyrolysis or creation of a slurry), and injecting it into geologic storage.

SECTORS

- **Sink** activity in land sector
- **Removal** in land sector via photosynthesis
- **Storage** activity similar to CO_2 transport and storage, but could interface with a variety of sectors (e.g. waste, croplands, etc.)

KEY UNCERTAINTIES

- Market-mediated land use effects (captured in existing land-sector inventory)
- Degradation and movement of biomaterial
- GHG leakage
- Storage monitoring and maintenance

Biomass burial

Using photosynthesis to remove CO_2 from the atmosphere, and storing the resulting biomass to prevent or slow decomposition.

SECTORS

- **Sink** activity in land sector
- **Removal** in land sector via photosynthesis
- **Storage** activity similar to landfills, but could interface with a variety of sectors (e.g. waste, croplands, etc.)

KEY UNCERTAINTIES

- Market-mediated land use effects (captured in existing land-sector inventory)
- GHG leakage
- Storage monitoring and maintenance
- *Soil organic carbon impacts (captured in existing soil inventory)*

Novel approaches will continue to emerge

Reporting frameworks developed for carbon removal should anticipate an expanding universe of approaches. Examples of ongoing projects that are not mentioned in the background paper include:

- Biogenic CO_2 capture at pulp & paper mills or landfills
- Enhanced weathering in wastewater treatment plants
- Direct ocean carbon removal
- Biomass sinking
- ...

Temporal dynamics are critical — and uncertain

Consistent reporting will require fair treatment of the temporal dynamics that relate the sink activity to the actual carbon removal. Patterns to consider include:

- Expected storage degradation (e.g. biochar)
- Unexpected leakage or storage failure (e.g. DAC, BECCS, biomass burial)
- Gradual removal (e.g. enhanced weathering and ocean alkalinity enhancement)

Thank you

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REFERENCES

- CarbonPlan and Frontier (2023) “CDR Verification Framework”. CarbonPlan 10.5281/zenodo.10895244
- Kukla et al. (2024) “Does enhanced weathering work? We’re still learning.” CarbonPlan https://carbonplan.org/research/enhanced-weathering-fluxes
- Zhou et al. (2024) “Mapping the global variation in the efficiency of ocean alkalinity enhancement for carbon dioxide removal“ https://doi.org/10.21203/rs.3.rs-4124909/v1 (under review)