



**CARBON
SOLUTIONS**

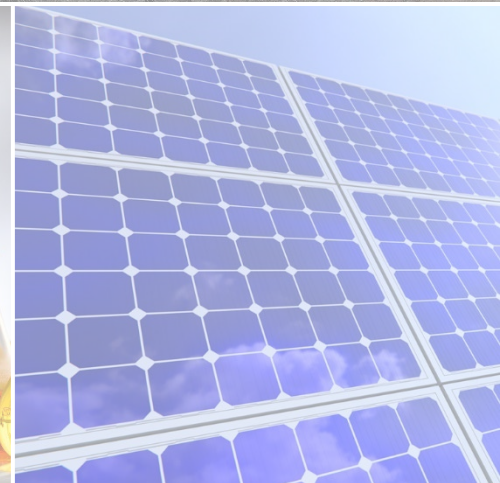
Designing CCS Infrastructure to Meet National Goals

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CARBON SOLUTIONS

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Mission-driven low-carbon business

- CARBON SOLUTIONS works with industry, government, non-profits, researchers, & other stakeholders to identify & implement real-world solutions for low-carbon energy challenges.

History

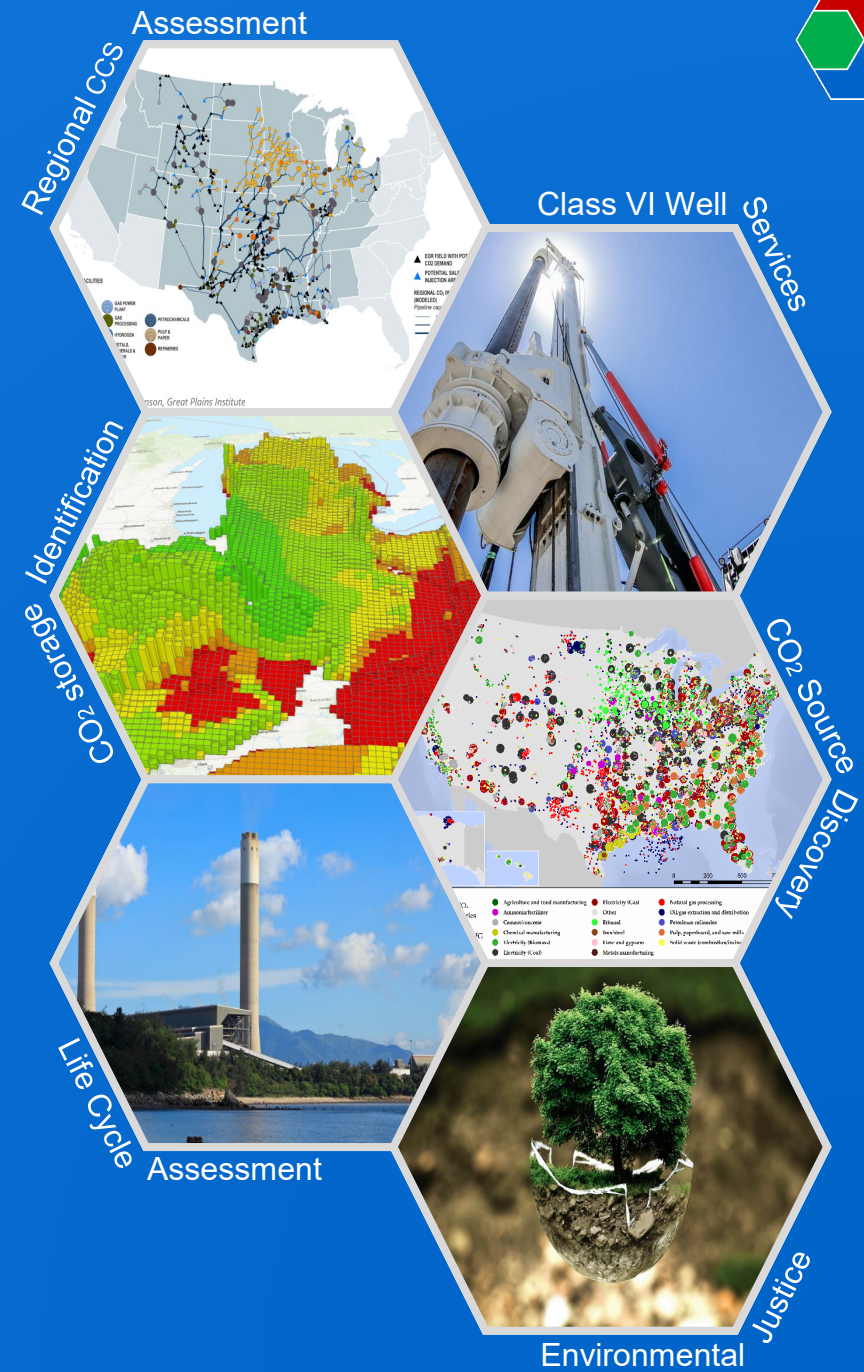
- Launched 2021 | ~35 employees | 60+ projects.
- Research | Consulting & Services | Software Development.
- **FUNDING:** 70% Fed. | 15% NGOs | 15% Industry.

Energy applications

- CCS, hydrogen, direct air capture, geothermal, wind, energy storage, grid modeling,, energy equity, environmental justice...

Data analytics

- Optimization, reservoir simulation, ML/AI, LCA, TEA, econometrics, GIScience...





US net-zero studies

- Gigatonne scale.
- Up to 1.7–2.0 GtCO₂/yr.
- 1,000s of sources.
- >100,000 km of pipeline.
- 1,000s of Class VI wells.
- 100-fold expansion.

CCS scale challenge

1. National infrastructure.
2. Carbon deserts.
3. Regional storage hubs.

Three studies

1. Decarbonize US fossil electricity.
2. Decarbonize US industrial sectors.
3. Mid-Atlantic industries & offshore storage



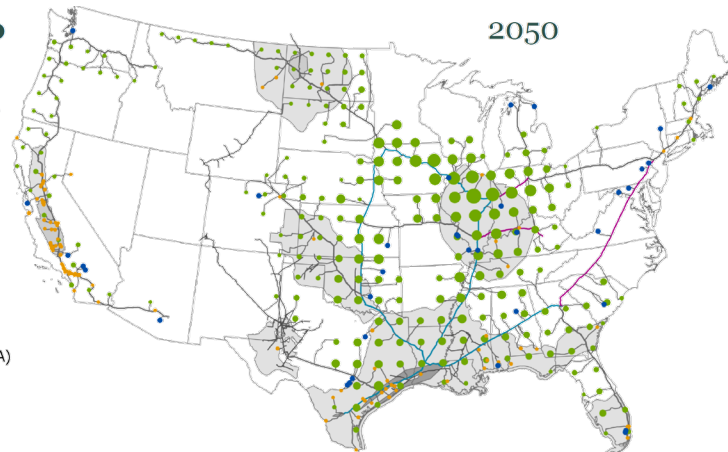
E-B+ scenario

1,361 million tCO₂/y
111,000 km pipelines
Capital in service: \$220B

- CO2 point source type
- CO2 point sources
 - BECCS - power and fuels
 - Cement w/ CCS
 - Natural gas power CCS oxyfuel

- CO2 captured (MMTPA)
- 0.0006449
 - 7.9144
 - 15.8282
 - 23.7419

- Trunk lines (capacity in MMTPA)
- < 100
 - 100 - 200
 - > 200



Integrated CCS assessment

- Simultaneously understand CO₂ capture, transport, & storage.

CO₂ Capture

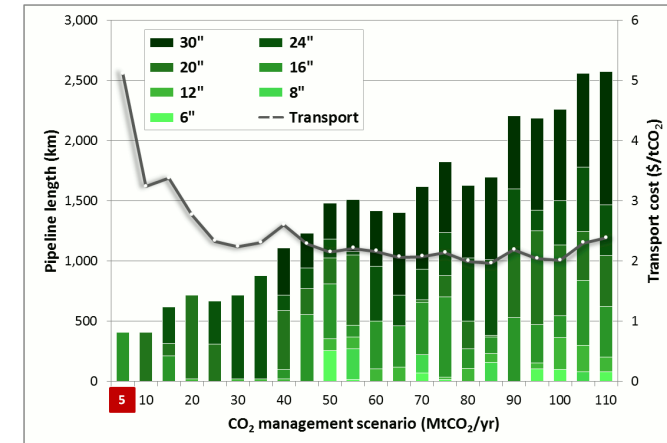
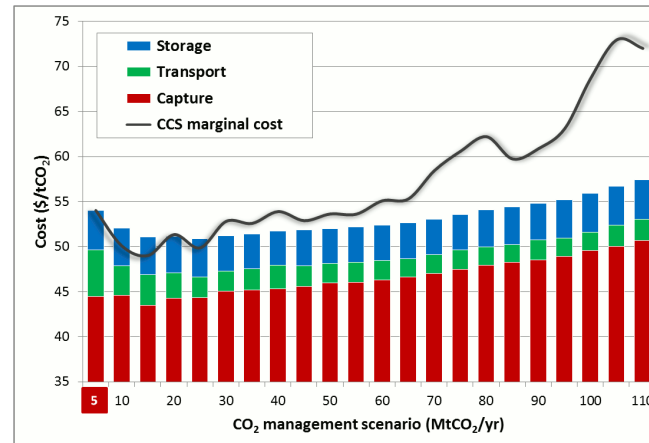
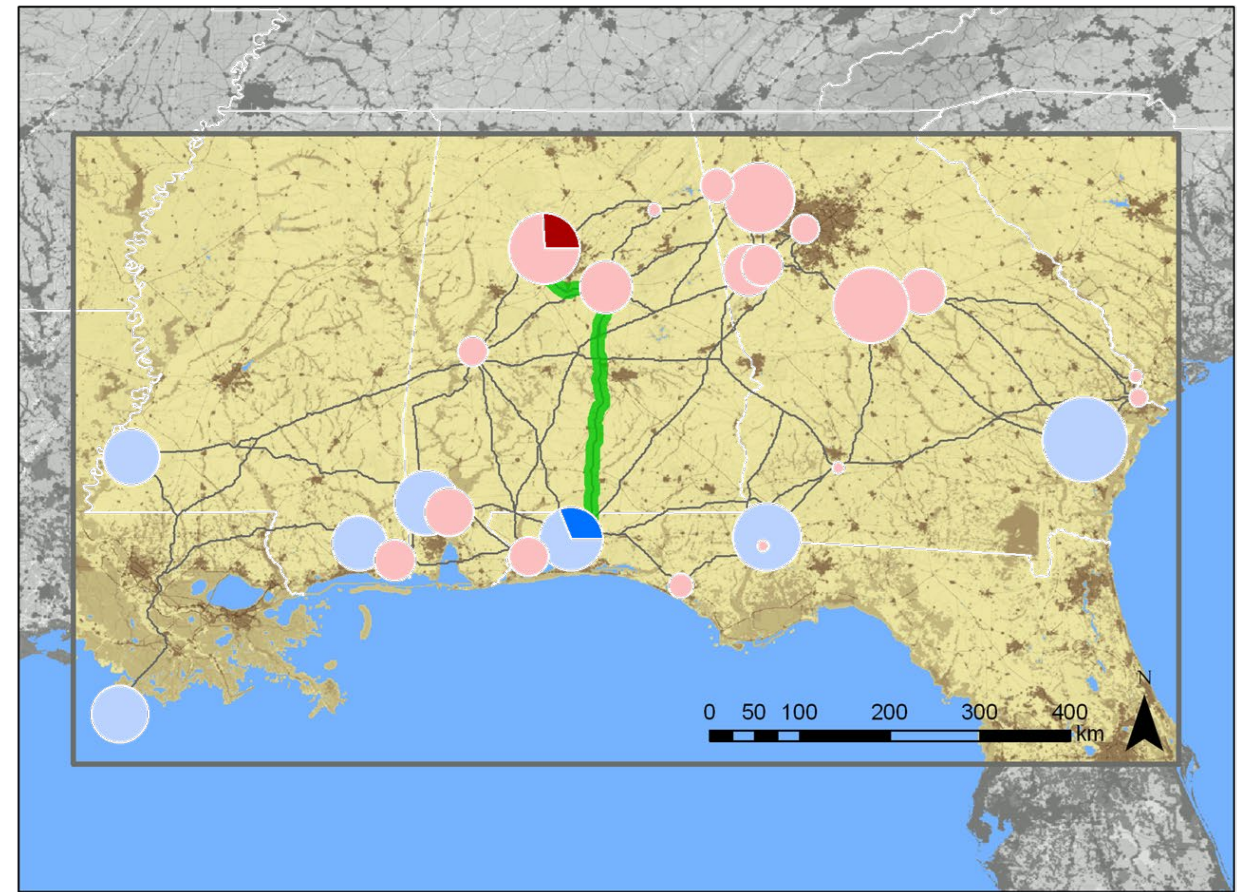
- Emissions, capturable CO₂, purity by multiple streams, economics over space & time.

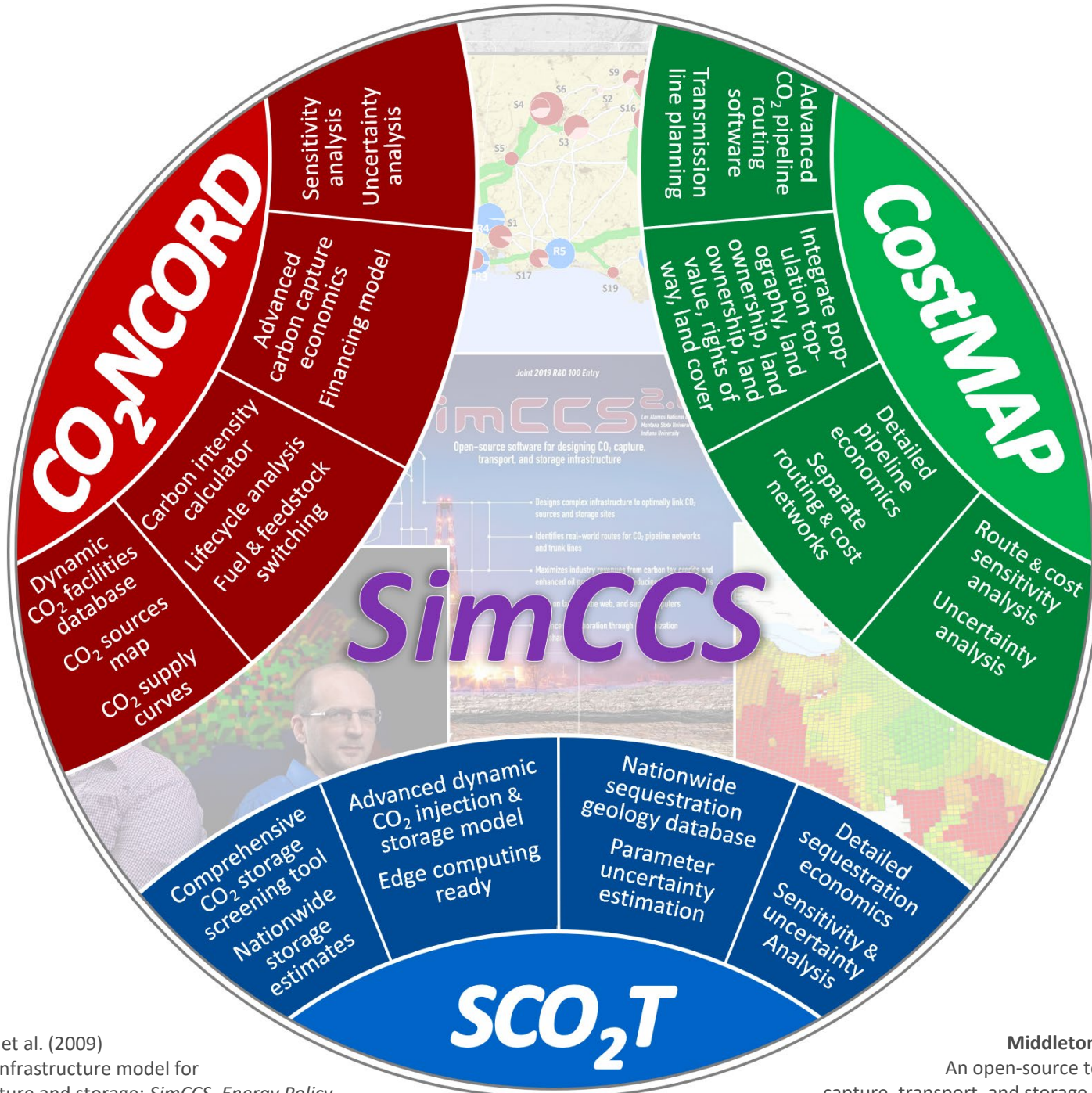
CO₂ Transport

- **ROUTES:** Potential routes considering multi-dimensional geographies.
- **PIPELINES:** Capacities, trunklines to aggregate CO₂, economics (capital, fixed & variable O&M).

CO₂ Storage:

- **STORAGE:** Identify ideal sites, dynamic CO₂ injection & storage, lifetime reservoir costs (injection, storage, & PISC).
- **UTILIZATION:** Oil, shale gas, geothermal, & materials.



**SimCCS^{PRO} | ANALYSIS**

- Decision support across the CCS value chain.

CO₂NCORD | CAPTURE

- Dynamic, customizable CO₂ capture database.

CostMAP^{PRO} | TRANSPORT

- Multiscale, multi-attribute pipeline routing.

SCO₂T^{PRO} | STORAGE

- Advanced tool for dynamic CO₂ storage & costs.



Why?

- Commercial-scale CO₂ capture opportunities.

How?

- **FUSE:** emissions data from EPA GHGRP/FLIGHT, EPA eGRID, RFA (ethanol)...
- **Fuse:** capture cost & stream data from 15+ lit. sources.
- **EXPERTISE:** industry-leading experience with CO₂ capture.

What?

- **GEODATABASE:** source locations, CO₂ streams (quantity & purity), & capture costs.
- **SUPPLY CURVES:** Identify economic opportunities.
- Market Assessment.

CO₂NCORD

The CO₂ National Capture Opportunities and Readiness Database

Industry Categories (Primary + Secondary)

Mineral Processing

- Lime
- Cement
- Soda Ash
- Gypsum
- Other

Chemical Manufacturing

- Ammonia
- Fertilizer
- Hydrogen
- Other

Electricity

- Coal
- Biomass
- Natural Gas
- Other Electricity

Petrochemicals

- Ethylene
- Ethylene Oxide
- Other

Metals

- Iron and Steel
- Aluminum
- Other

Mining

- Fluid Extraction
- Solid Extraction

Solid Waste

- Incineration
- Other (Landfill and Recovery)

Facilities and Equipment

- Other Gas-fired Facilities/Equipment
- Pipeline Facilities

Manufacturing

- Ethanol
- Food and Agricultural Products
- Other

Pulp, Paper, and Wood Products

- Pulp and Paper Mills
- Other Paper Products

Natural Gas (NG) Processing

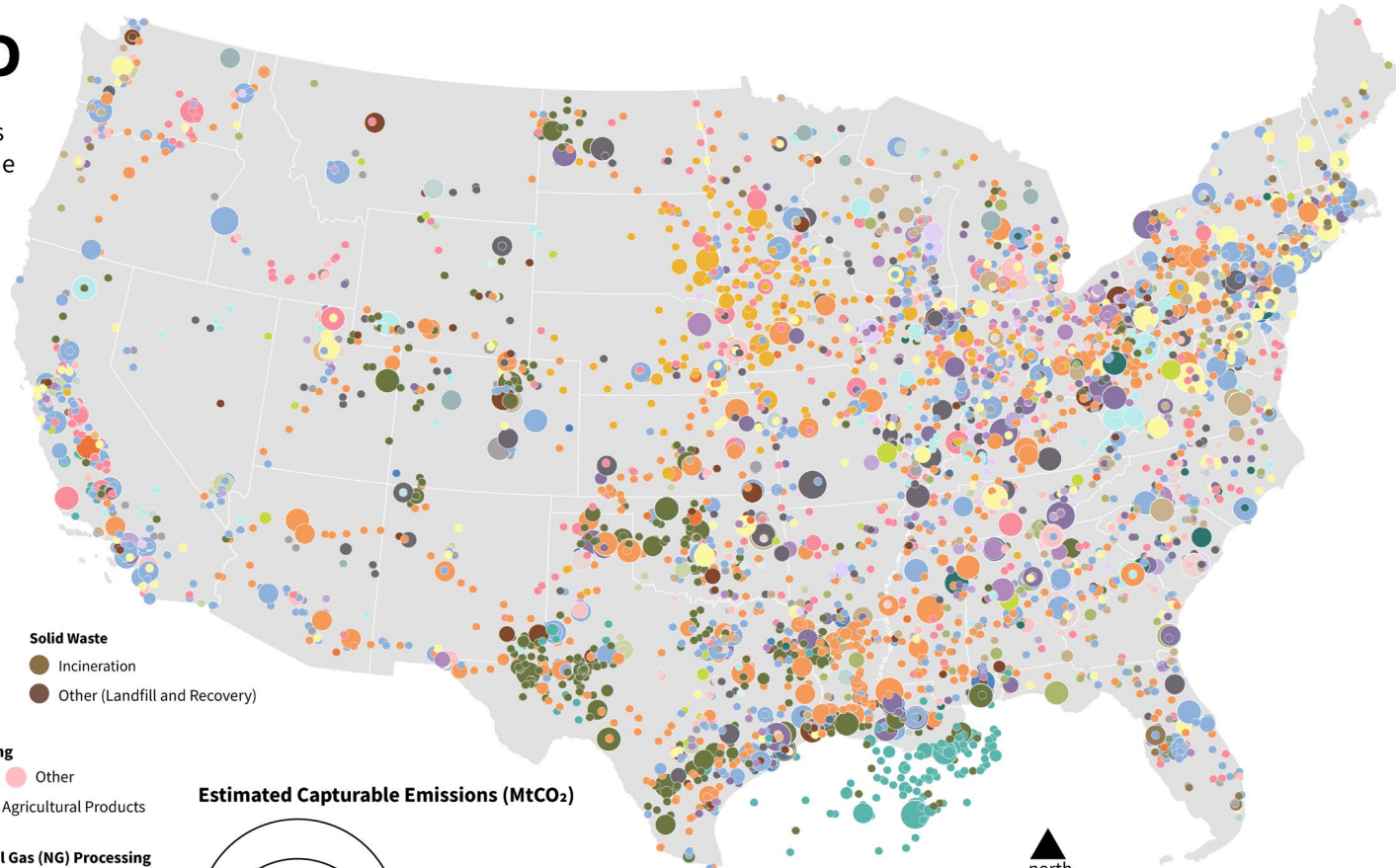
- Natural Gas Processing Plants (NGPP)

Petroleum Refineries

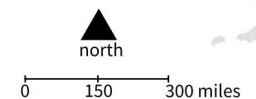
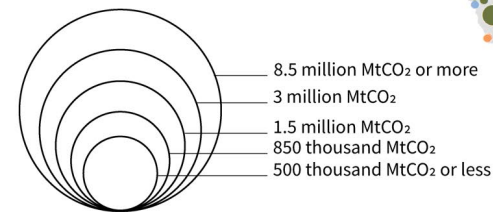
- Petroleum Products

Miscellaneous

- Other



Estimated Capturable Emissions (MtCO₂)



Why?

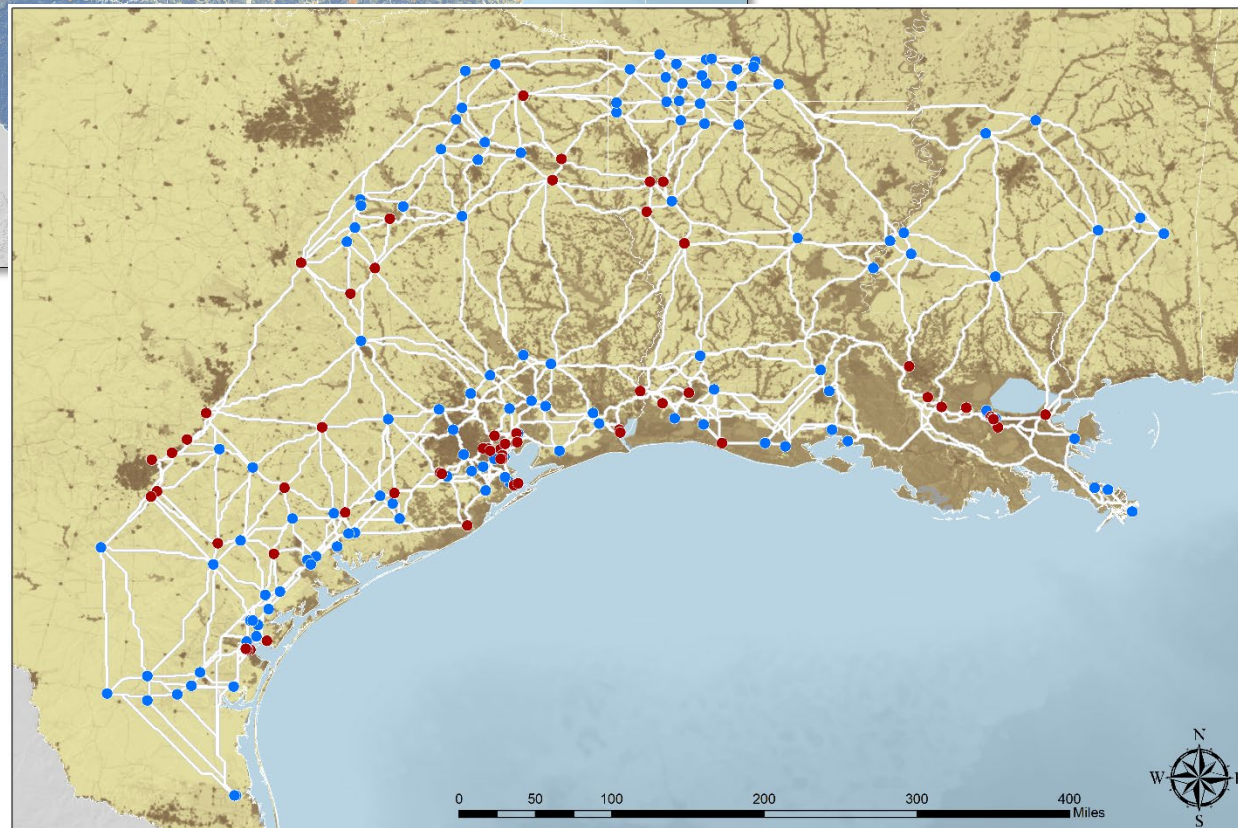
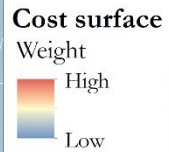
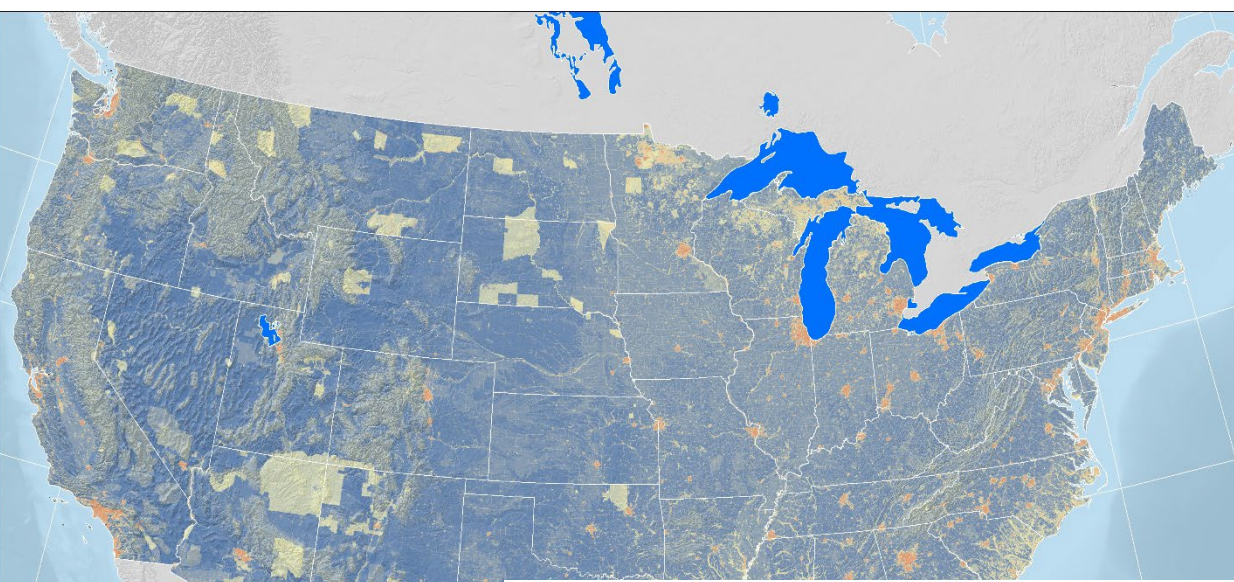
- Understand where, how, & cost of CO₂ transportation.

How?

- Nonlinear integration of ROWs (e.g., pipelines), barriers (e.g., rivers), population, topography, land use, ownership, EJ...
- *SimCCS* cost model.

What?

- Next-generation software for pipeline costs & routing.
- Cost & routing surfaces, grid cells 10 m to ~1,000 m.
- Multiple pipeline routes, avoid sensitive areas, dispersion plumes.
- Pipeline route robustness.



Hoover et al. (2020) *CostMAP*: an open-source software package for developing cost surfaces using a multi-scale search kernel, *International Journal of Geographical Information Science*.

Why?

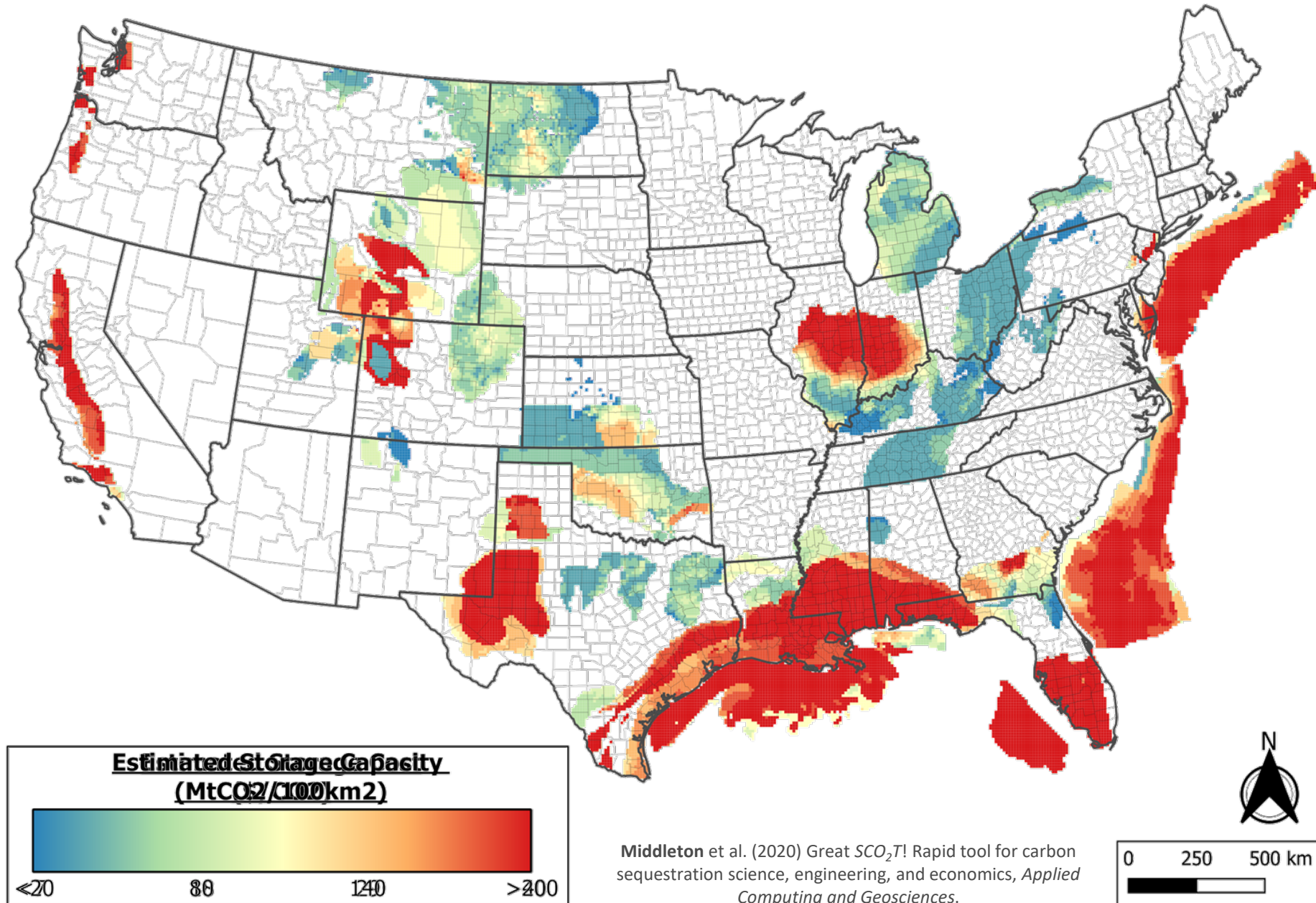
- Rapidly calculate realistic injection, storage & costs.

How?

- Machine learning for CO₂ sequestration that connects dynamic CO₂ injection & storage with economics.
- Best US-wide sequestration geology.

What?

- Tool to rapidly calculate dynamic CO₂ injection, storage & costs (1000s of realizations per second).
- Regional storage screening.



Middleton et al. (2020) Great SCO₂T! Rapid tool for carbon sequestration science, engineering, and economics, *Applied Computing and Geosciences*.

STUDY 1

Decarbonize post-2030
fossil power

Study Design

Source parameters

- **Fuels:** All coals, NG.
- **Min capture:** 0.5 MtCO₂/yr.
- **Capture rate:** 90%.
- **Retirements:** 2030.
- **Capacity factor:** 30%.

Sources

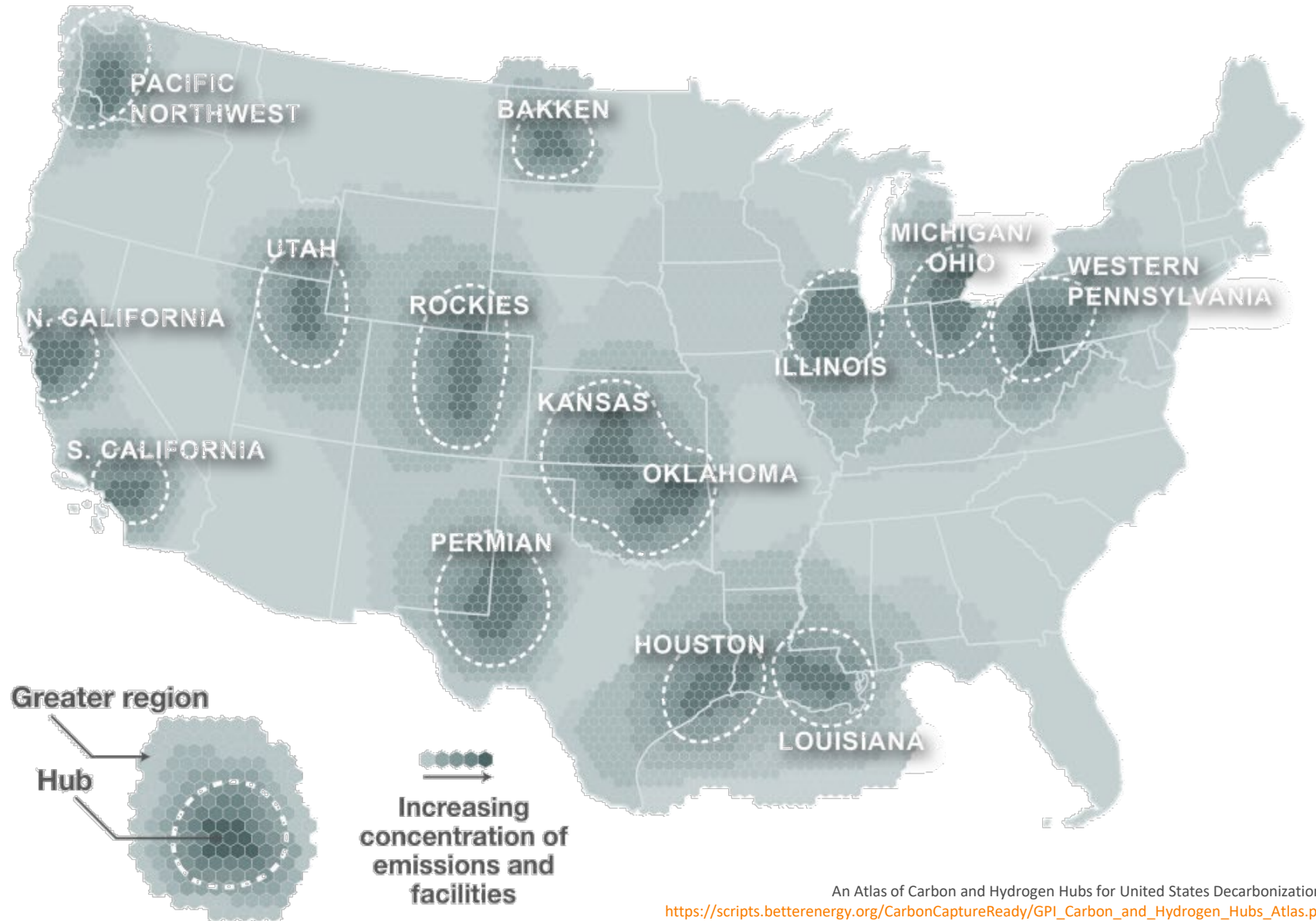
- 429 plants | 1,044 MtCO₂/yr.
- 136 coal | 600 MtCO₂/yr.
- 293 NGCC | 444 MtCO₂/yr.

Storage

- Saline, onshore only.
- 14 hubs, 371 SCO₂T sites.

Scenario

- Capture 200 | 400 | 600 | 800 | 1,000 | 1,044 MtCO₂/yr.



An Atlas of Carbon and Hydrogen Hubs for United States Decarbonization :
https://scripts.betterenergy.org/CarbonCaptureReady/GPI_Carbon_and_Hydrogen_Hubs_Atlas.pdf



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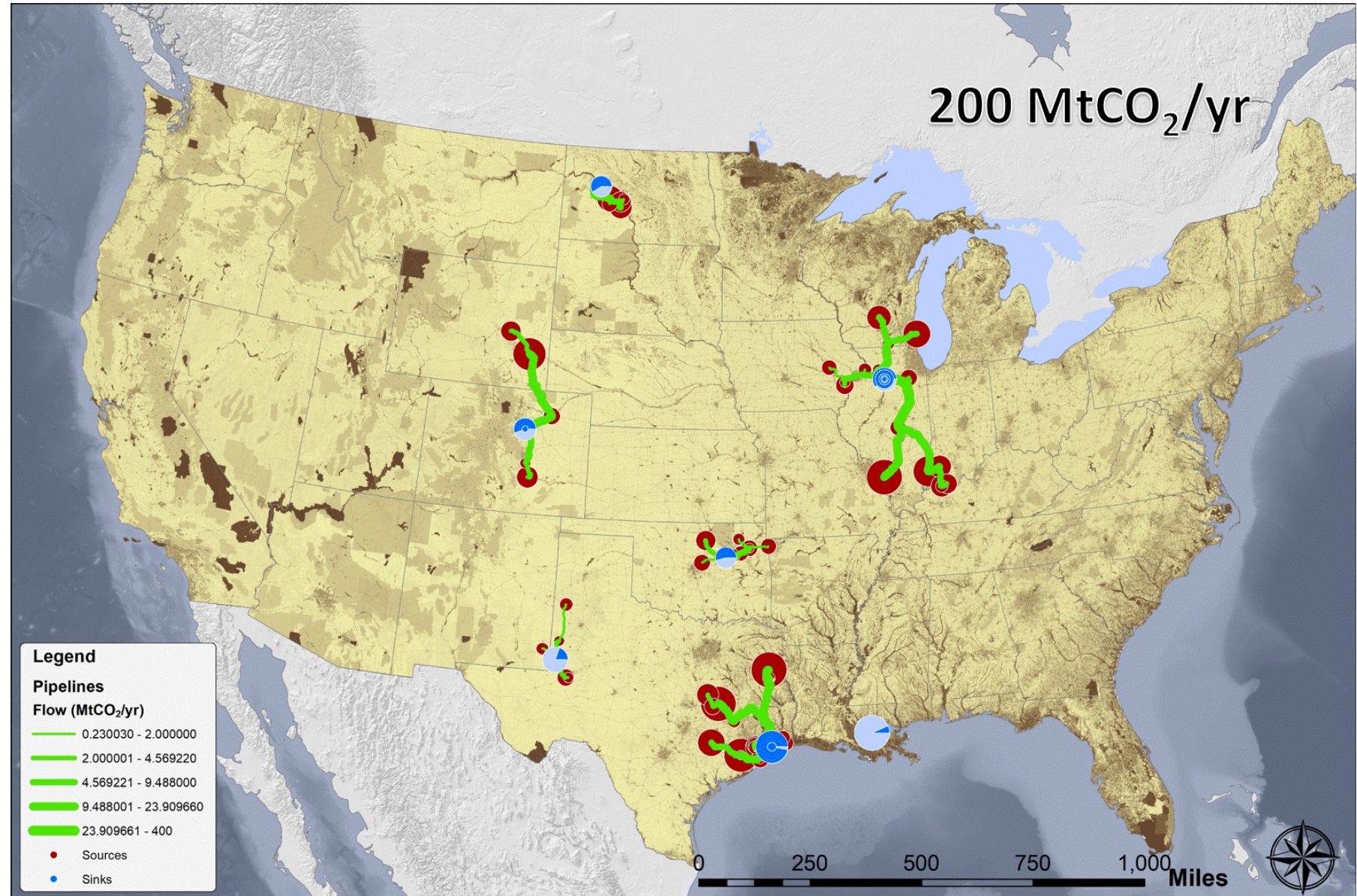
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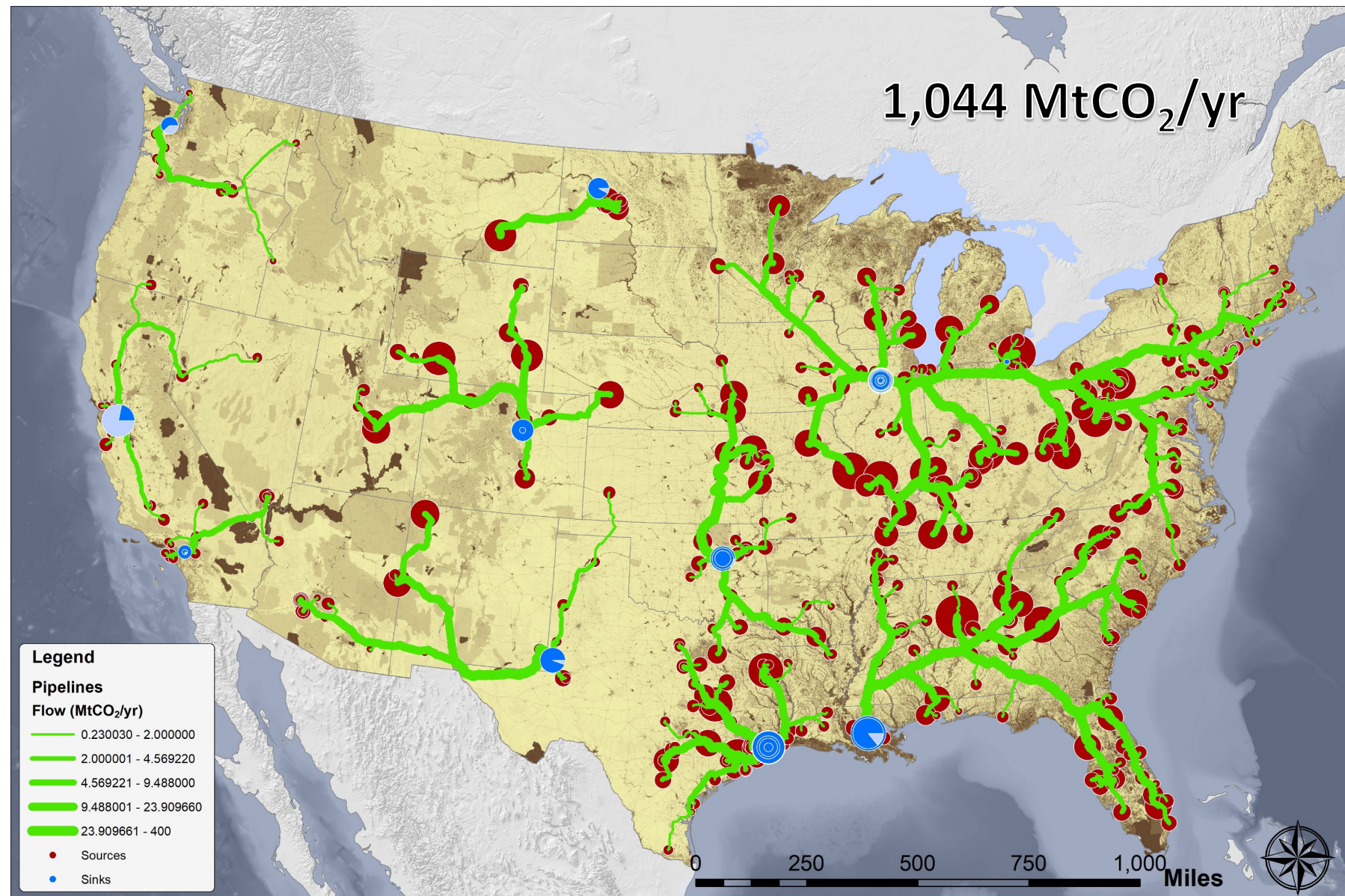
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Distributed vs. Centralized Storage



Distributed Scenarios

Target (MtCO ₂ /yr)	# Sources	# Sinks	# Hubs	Network Length (km)	Total Cost (\$/tCO ₂)				Marginal Cost (\$/tCO ₂)			
					Total	Capture	Transport	Storage	Total	Capture	Transport	Storage
200	43	32	-	2,133	79.22	68.30	2.24	8.68	79.22	68.30	2.24	8.68
400	102	64	-	5,147	80.97	69.02	3.18	8.76	82.71	69.75	4.12	8.84
600	183	96	-	9,627	82.23	69.60	4.08	8.55	84.76	70.75	5.88	8.12
800	260	120	-	16,064	83.63	69.78	5.28	8.57	87.84	70.31	8.89	8.64
1,000	389	142	-	27,814	85.99	70.26	7.15	8.58	95.41	72.20	14.60	8.61
1,044	429	146	-	32,550	86.92	70.37	8.04	8.52	108.06	72.74	28.26	7.05

Centralized Scenarios

Target (MtCO ₂ /yr)	# Sources	# Sinks	# Hubs	Network Length (km)	Total Cost (\$/tCO ₂)				Marginal Cost (\$/tCO ₂)			
					Total	Capture	Transport	Storage	Total	Capture	Transport	Storage
200	66	14	8	4,773	84.27	69.56	6.64	8.07	84.27	69.56	6.64	8.07
400	122	26	12	10,038	85.51	69.30	7.79	8.42	86.75	69.04	8.94	8.77
600	175	29	13	16,458	87.38	69.26	10.02	8.10	91.12	69.17	14.49	7.46
800	266	33	13	24,736	88.72	69.71	10.94	8.07	92.74	71.06	13.70	7.98
1,000	388	38	13	35,291	91.52	70.25	13.20	8.07	102.71	72.41	22.23	8.07
1,044	429	38	13	40,361	92.13	70.37	13.68	8.09	106.15	73.04	24.63	8.49

STUDY 2
All 45Q-eligible
industrial facilities



Source parameters

- **Sectors:** Ammonia, hydrogen, ethanol, aluminium, iron & steel, cement, lime, natural gas processing, ethylene, petrochemicals, pulp & paper.
- **Min:** 12,500 tCO₂/yr.

Sources

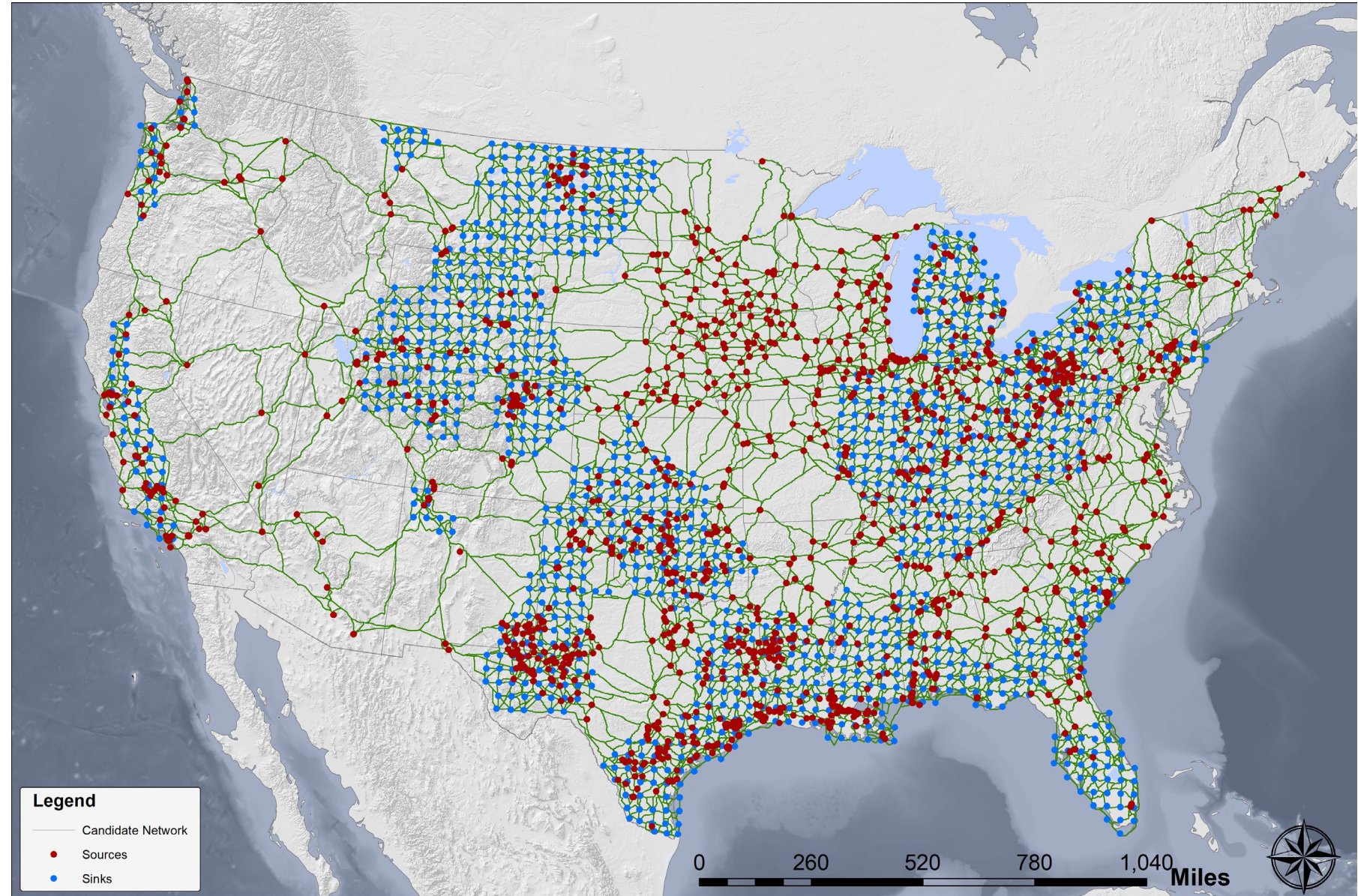
- **All streams:** 2731.
- 532 MtCO₂/yr.

Storage

- Saline, onshore only.

Scenario

- **Scenario A:** *SimCCS^{CAP}* (capture all CO₂).
- **Scenario B:** *SimCCS^{PRICE}* (profitable under 45Q).



Scenario A: All CO₂ Captured



Capture target

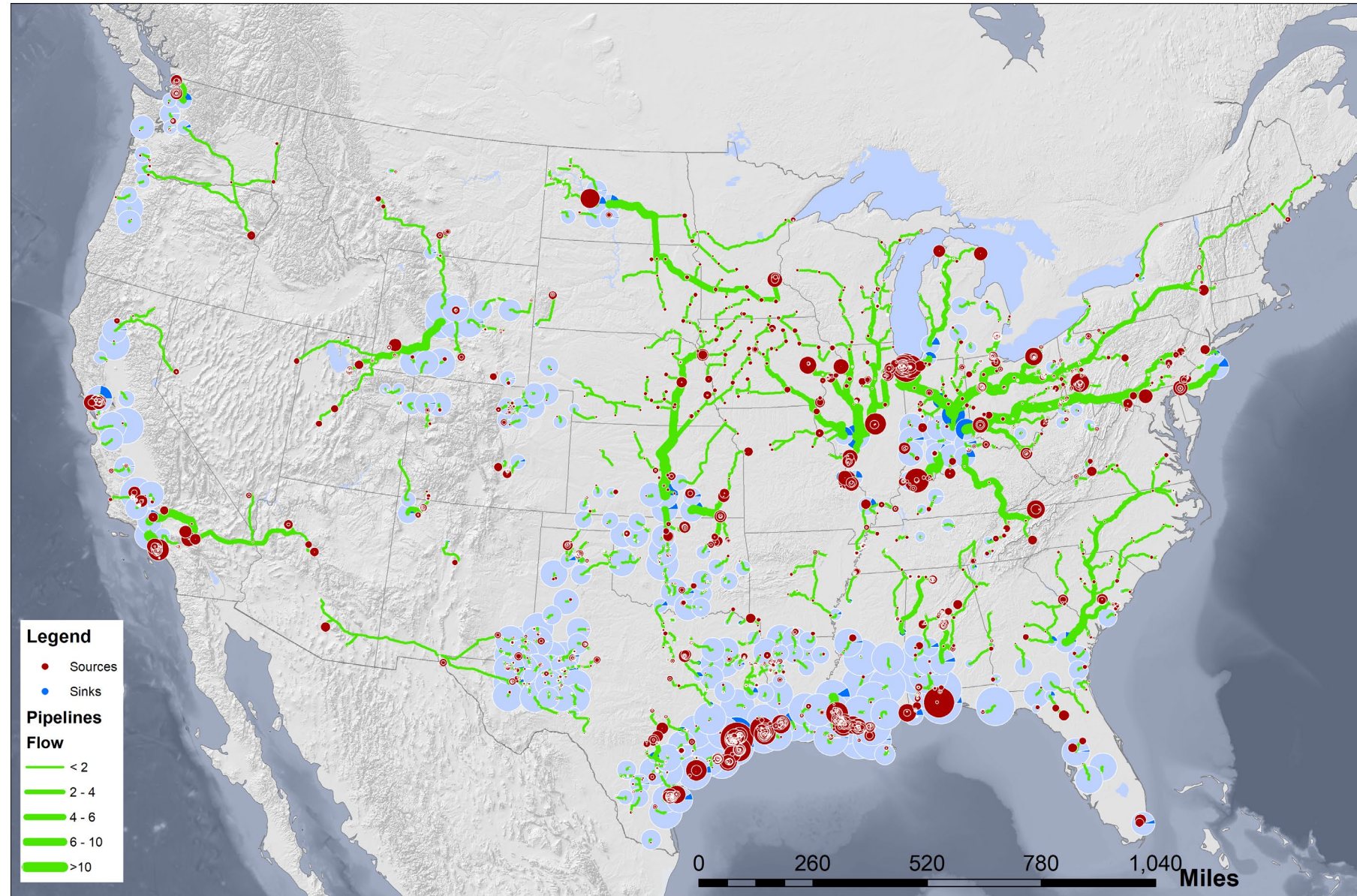
- 532 MtCO₂/yr.

Infrastructure

- **Captured:** 532 MtCO₂/yr.
- **# sources:** 2731.
- **# sinks:** 329.
- **Network:** 62,703 km.

Costs

- **Capture:** \$65.31/tCO₂.
- **Transport:** \$18.83/tCO₂.
- **Storage:** \$9.23/tCO₂.
- **Total:** \$93.37/tCO₂.



Scenario B: Profitable Under 45Q



Capture target

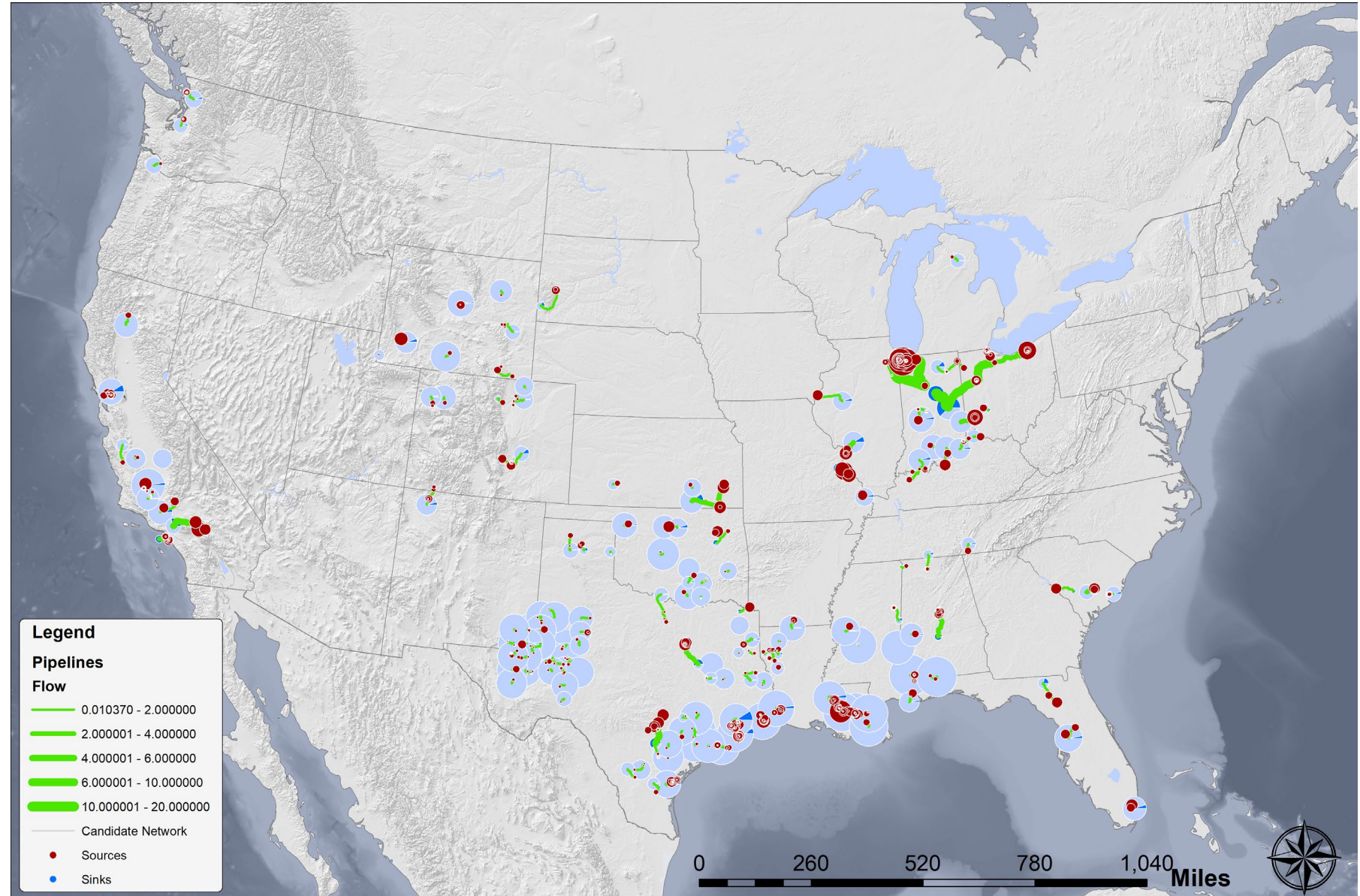
- 45Q: \$85/tCO₂.

Infrastructure

- **Captured:** 176 MtCO₂/yr.
- **# sources:** 522 (2731).
- **# sinks:** 143.
- **Network:** 9,317 km.

Costs

- **Capture:** \$47.53/tCO₂.
- **Transport:** \$6.94/tCO₂.
- **Storage:** \$9.60/tCO₂.
- **Total:** -\$21.11/tCO₂.



STUDY 3

**Mid-Atlantic industries
& offshore storage**

Offshore Storage

Source parameters

- **Sectors:** Ammonia, hydrogen, ethanol, aluminium, iron & steel, cement, lime, natural gas processing, ethylene, petrochemicals, pulp & paper.
- **Min:** 12,500 tCO₂/yr.

Sources

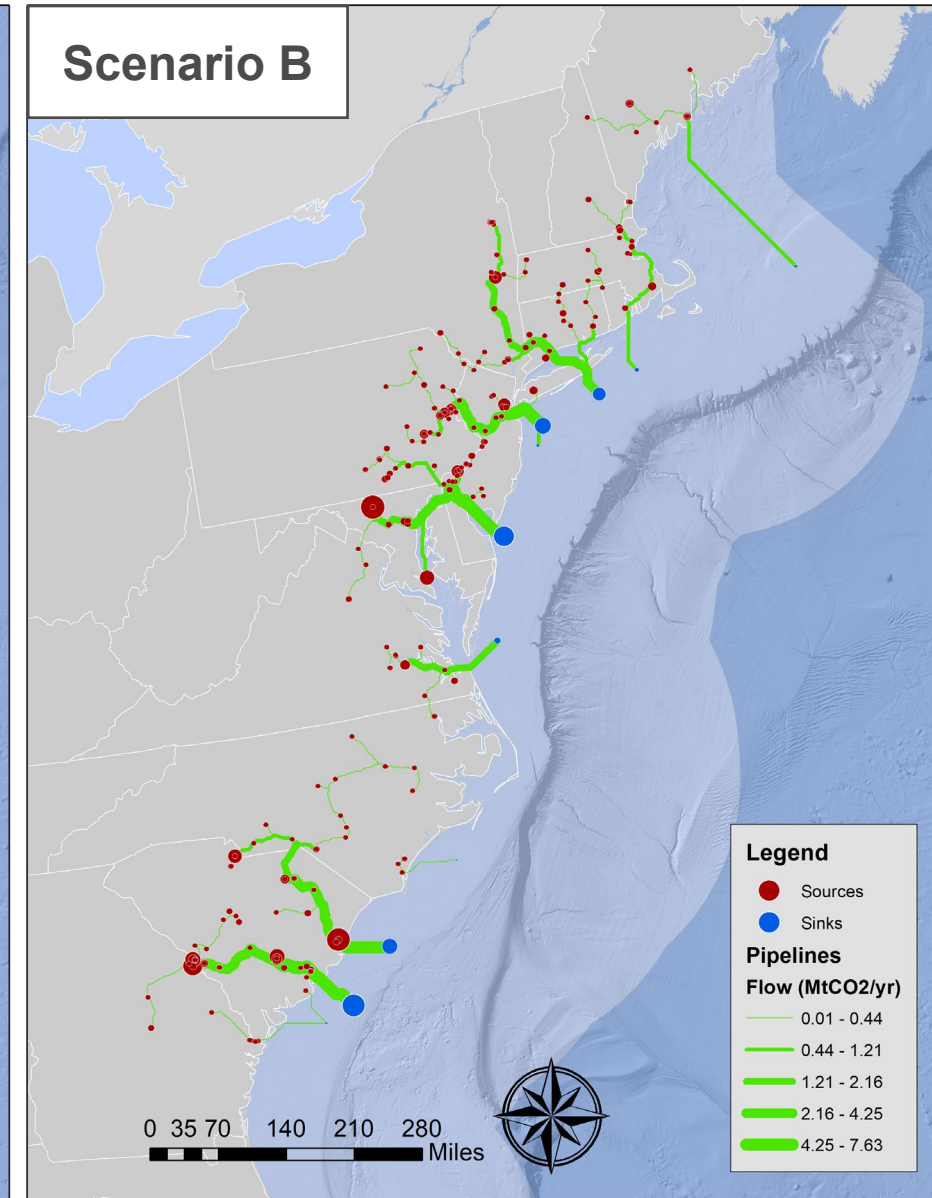
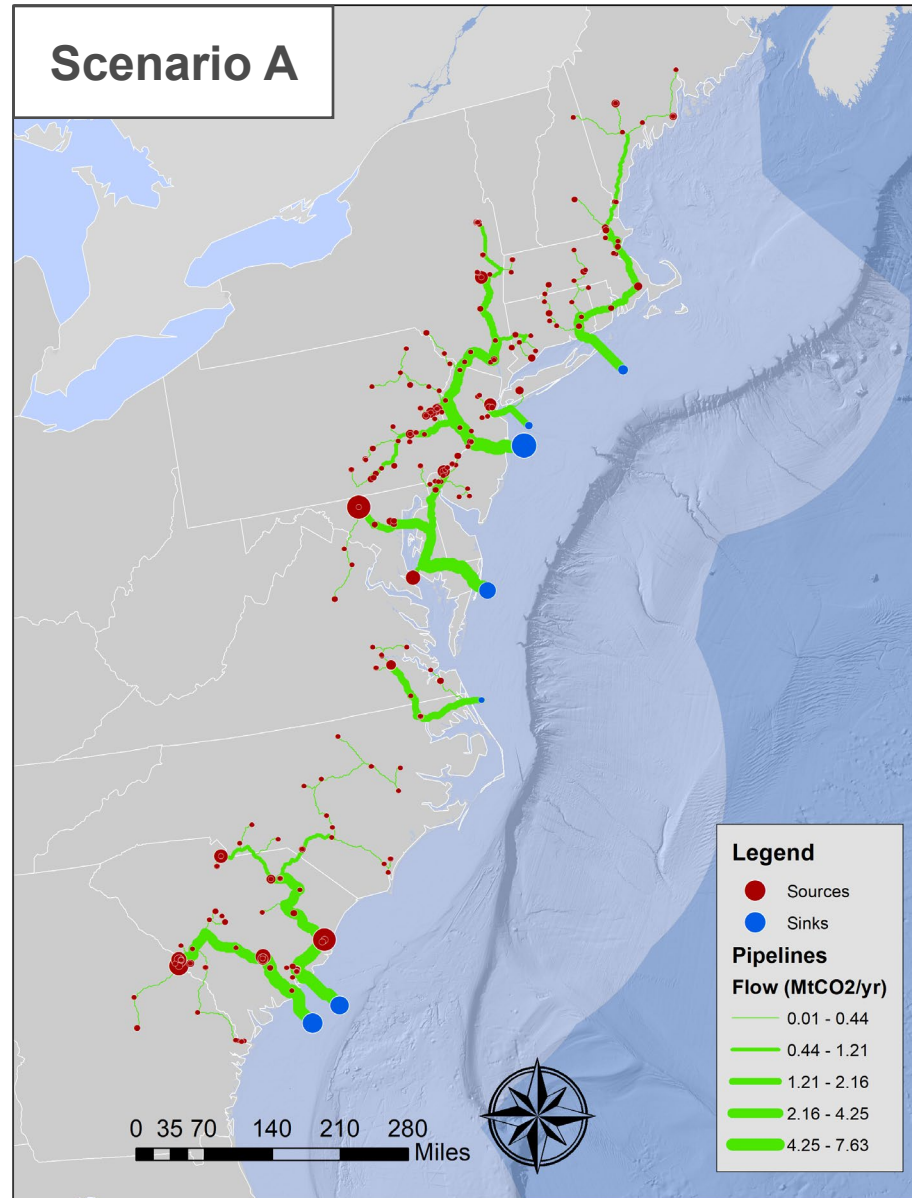
- **Sources:** 199
- **Streams:** 263.
- **Supply:** 31.5 MtCO₂/yr.

Storage

- Saline, offshore only.

Scenario

- **SimCCS^{CAP}** (capture all CO₂).
- **Scenario A:** Let model choose best pipeline route.
- **Scenario B:** Emphasize offshore transport.



Take Home Message

Why?

- Understand CCS at scale (net zero) using best possible data & models.
- Identify challenges & opportunities.
- Assess required storage requirements.

How?

- *SimCCS^{PRO}* software tools/databases.

What?

- **National infrastructure:** Massive CCS challenge to meet net zero targets.
- **Carbon deserts:** Areas without good storage but still must decarbonize.
- **Regional storage hubs:** Distributed storage is relatively abundant & requires less CO₂ transport.

