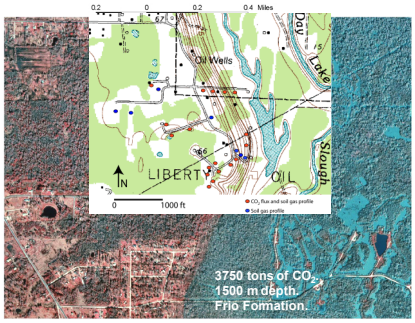
Geologic CO_2 Storage Verification Monitoring: Preliminary Results for the Frio Pilot Test

Curtis M. Oldenburg
Jennifer L. Lewicki

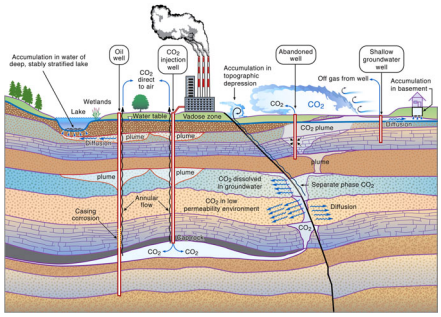
Earth Sciences Division

NETL Third Annual Conference on Carbon Capture and Sequestration
Alexandria, VA
May 3-6, 2004

South Liberty Site (Frio Pilot Study)



CO_2 Leakage Risk Motivates Verification



Introduction

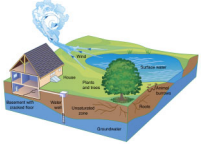
- Injection of CO_2 into deep geologic formations involves risk that CO_2 will migrate away from primary target.
- Verification of CO_2 sequestration integrity is needed to satisfy concerns about:
  - Health, Safety, and Environmental (HSE) risk
  - Costs of sequestration (energy, emissions, dollars)
- Verification involves field monitoring and measurements.
- Technology to measure CO_2 concentrations and fluxes is well established.
- However, the challenge is that CO_2 is naturally ubiquitous.

Outline

- Terminology.
- Predicted CO_2 Leakage Or Seepage Signal (LOSS).
- Controls on background fluxes and concentrations.
- Near-surface monitoring technologies.
- Strategies for CO_2 storage verification.
- Example work in progress.

Terminology

- Leakage = CO_2 migration away from primary sequestration target.
- Seepage = CO_2 transport out of the ground into the atmosphere or into surface water.
- Surface layer = bottom 1/10 of the atmospheric boundary layer
- Near-surface environment = ~ 10 m depth – ~ 10 m height.
- LOSS = Leakage Or Seepage Signal

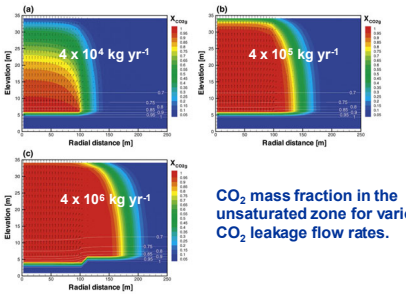


Expected Concentrations and Fluxes

- Case-studies of geologic CO_2 sequestration leakage are lacking.
- Therefore, we turn to modeling to predict expected behavior.
  - (1) CO_2 attenuation in the unsaturated (aka vadose) zone.
  - (2) Atmospheric dispersion of CO_2 in the surface layer.

- Leakage can lead to high CO_2 concentrations in the subsurface.
- Atmospheric dispersion is effective at dispersing seeping gases.
- However, CO_2 concentrations may be higher in stagnant (low-wind) areas.
- CO_2 concentrations can also be higher for higher fluxes.

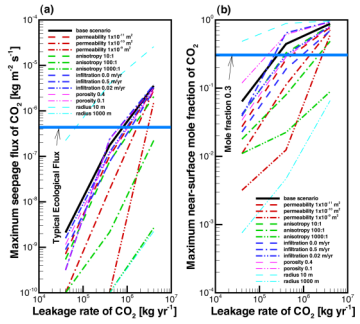
CO_2 Migration Through 30 m of Unsaturated Zone with Infiltration 10 cm yr^{-1}



CO_2 mass fraction in the unsaturated zone for various CO_2 leakage flow rates.

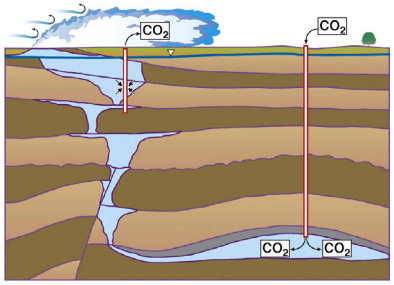
(Oldenburg and Unger, *Vadose Zone Journal*, 2, 287–296, 2003)

Sensitivity of CO_2 Seepage and Soil Gas Concentration to Various UZ Properties

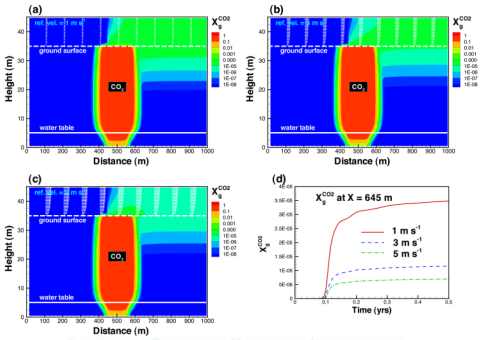


(Oldenburg and Unger, *Vadose Zone Journal*, 2, 287–296, 2003)

CO_2 Leakage, Seepage, and Dispersion



X_g^{CO2} in Subsurface and Surface Layer

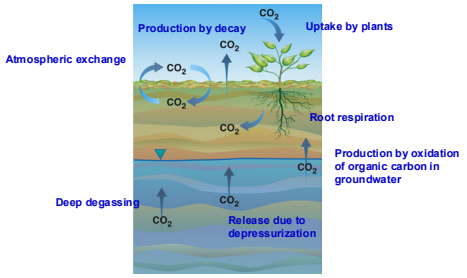


Modeling Summary

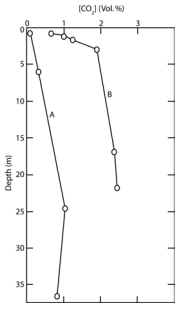
- Even for small leakage fluxes, subsurface CO_2 concentrations can be high.
- Diffuse seepage leads to passive dispersion in the surface layer.
- Atmospheric dispersion is effective at dispersing seeping gases, subject to caveats, among which are:
  - CO_2 concentrations will be higher in stagnant (low-wind) areas.
  - CO_2 concentrations will be larger for higher fluxes.
  - CO_2 concentrations may be higher periodically.

- Result is small LOSS in surface layer.
- Larger LOSS in the subsurface.

Natural CO_2 Sources and Sinks

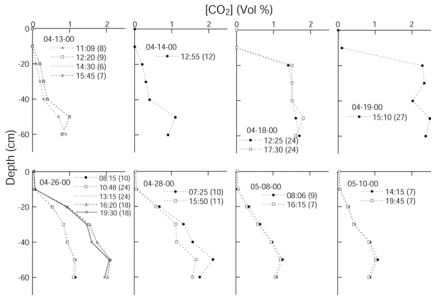


Measured CO_2 Profiles



(modified from Wood and Petraitis, *Water Resour. Res.*, *20*, 1193–1208,1984)

Temporal Changes in CO_2 Profile

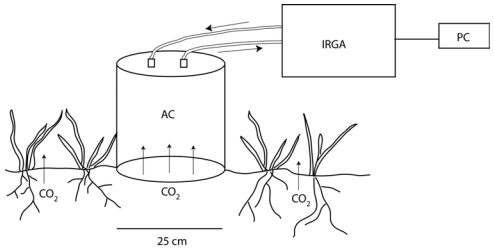


(modified from Lewicki et al., *J. Geophys. Res.*, *108*, 2003)

Overview of Approaches for Monitoring

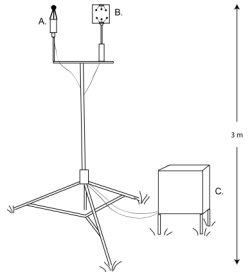
- Conventional CO_2 Monitoring Technologies:
  - IRGA (infrared gas analyzer) for point measurements of CO_2 in gas.
    - Absorption at 4.26 μm.
    - Frequency 1-10 Hz.
    - Typically 0–3000 ppmv detection range, also up to 100% CO_2.
    - Precision +/- 0.2 ppmv at 350 ppmv.
    - $5–30k.
    - Transportable.
    - Although point measurement, can be combined with other instrumentation to measure fluxes over small (accumulation chamber) and large (eddy correlation) areas.

Schematic of Accumulation Chamber (AC)



Soil gas is circulated and CO_2 concentration recorded every 1 sec.
Rate of accumulation of CO_2 in AC is measured.
Flux is calculated from rate of accumulation of CO_2.

Schematic of Eddy Correlation (EC) Tower



Time averaging of fluctuating CO_2 and vertical wind results in mean flux.
Mean flux is over an upwind footprint typically m^2 – km^2 in area.
Area of footprint is function of tower height and meteorological conditions.

Schematic of Truck-Mounted LIDAR

LIDAR = Light Detection And Ranging.
Raman LIDAR = detecting wavelength shifts due to Raman scattering.
DIAL = Differential Absorption LIDAR = tunable laser to create backscatter ratios.
Rapidly developing, good areal coverage.
Concentration integrated over path length.

Strategies for Storage Verfication

- Subsurface gas geochemistry.
  - — Carbon isotopes.
  - — Bulk soil gas composition.
    - Trends with depth. Spatial trends.
- Surface CO_2 concentration and flux monitoring.
  - — EC good for large areas and average flux measurements.
  - — AC good for small features and delineating spatial trends.
- Water chemistry.
  - — pH. Gas bubbles. Dissolved Inorganic Carbon.
- Integrated sampling strategy
  - — Baseline monitoring and modeling.
  - — Long-term monitoring.

Chemical and Isotopic Signatures

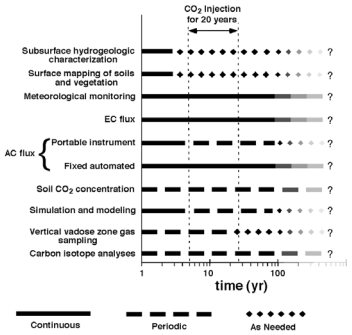
CO_2 source	$\delta^{13}C_{CO2}$ ‰	$\Delta^{14}C_{CO2}$ ‰	Near-surface CO_2 conc.	CO_2 conc. profile with depth	O_2 conc. profile with depth
Atmosphere	-7	-70	Low	–	–
Plant root respiration and oxidative decay of young soil organic matter	C_3: -24 to -38 C_4: -6 to –19	≥ -70	Low to moderate	Increasing through soil zone	Decreasing through soil zone
Oxidative decay of ancient organic matter	C_3: -24 to -38 Aquatic/C_4: -6 to –19 Also age dependent	Highly depleted to absent, depending on age	Low	Increasing potentially through vadose zone	Decreasing potentially through vadose zone
Marine carbonate rocks	0 ± 4	absent	Low	Increasing through vadose zone	No effect
Fossil fuel	Average: -27	absent	Moderate to high	Increasing through vadose zone	No effect

Conc., C_3, and C_4, refer to concentration, C_3 plants, and C_4 plants. All near-surface concentrations given are general estimates; these concentrations will be strongly dependent on the magnitude of the CO_2 flux.

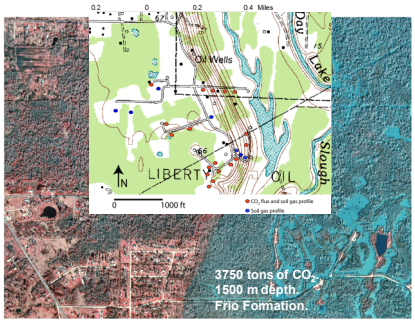
Integrated Sampling Strategy

- Baseline monitoring and modeling.
  - — Characterize spatial and temporal variability
    - Soil, parent material, vegetation, hydrology, topography, surface water, ...
  - — Flow modeling (TOUGH2) and ecological modeling (LSM).
- Surface CO_2 concentration and flux monitoring (AC and EC).
- Soil gas sampling and analysis. Fixed sites over time.
- Soil moisture and temperature.
- Goal is to understand the natural ecological system prior to injection.

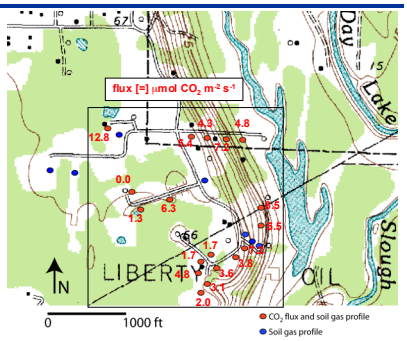
Potential Activities and Schedule



South Liberty Site (Frio Pilot Study)



CO_2 Flux Baseline Survey (AC)



1 μmol CO_2 m^{-2} s^{-1} = 4.4 x 10^{-5} kg CO_2 m^{-2} s^{-1}

Summary

- Extensive knowledge exists about behavior, properties, detection, and monitoring of CO_2.
- Modeling provides plausible expectations of CO_2 seepage flux and concentration.
- Nevertheless, discerning small CO_2 LOSS from natural background variation will be challenging.
- Strategy we propose involves comprehensive baseline monitoring and modeling to develop understanding of natural system.
- Program of multiple and integrated measurement and monitoring can be applied during and after injection.
- Measurements in conflict with expectations of the natural system would be investigated thoroughly by more detailed studies.

Acknowledgments

This work was supported in part by the Office of Science, U.S. Department of Energy, and by the Assistant Secretary for Fossil Energy, Office of Coal and Power Systems, through the National Energy Technologies Laboratory (NETL), and by Lawrence Berkeley National Laboratory under Department of Energy Contract No. DE-AC03-76SF00098 .