Near-Surface Monitoring at Geologic CO₂ Storage Sites

Presented by
Katherine Romanak,
The University of Texas at Austin
Bureau of Economic Geology
Gulf Coast Carbon Center/STORE

IEAGHG Summer School
Beijing, China
August 2012
One Geologist’s Story
One Geologist’s Story
Geologist’s Work in CCS
Presentation Outline

• Near-surface versus deep monitoring
• Challenges of near-surface monitoring
• Strategies and tools for near-surface leak detection
• Proving a negative
• Real life example
Potential CO$_2$ Migration Pathways
Brine Migration Pathways

- Brine leakage through faults/wells to the shallow subsurface
- Along-dip water displacement
Role of Monitoring in a CCS Project

1. Site Characterization-
   Primary means of protection. High level of assurance required for permitting.

2. Risk Assessment-
   Aided by modeling, identifies potential unwanted outcomes.

3. Project Design-
   Design injection to further minimize perceived risk.

4. Monitoring Plan
   - Deep subsurface: Verification Monitoring
     Does what happened conform to predictions?
   - Near-surface: Assurance Monitoring
     No unwanted outcomes.
Deep versus Near-Surface Monitoring

- **Deep (verification)**
  - Verify containment
  - Track movement of CO$_2$ and brine
  - Test models

- **Near-Surface (assurance)**
  - Detect a leak
  - Quantify any release to atmosphere
  - Assess environmental impacts
  - Address public concerns
Deep versus Near-Surface Monitoring

Near-Surface Monitoring Zone:
- Strong variability, dynamic, many challenges, release to atmosphere, biosphere impacts
- Moderate background variability, assurance of no damage to drinking water, easy access
- Minimal variability, early detection, small signals

Deep Monitoring Zone:
- Static, quiet environment, variability is from CO\textsubscript{2} injection, CO\textsubscript{2}/brine migration

Figure courtesy of Sue Hovorka
Near-Surface Monitoring: Advantages

- Accessible – inexpensive compared to deep monitoring
- Direct observation of resources
  - Groundwater
  - Biosphere
- Point of release to atmosphere
- Leakage quantification for carbon accounting
The near-surface is naturally CO$_2$-rich. CO$_2$ is variable in space and time ("noise"). It is hard to tell a leakage "signal" from background "noise".
“Signal” to “Noise”

Natural CO₂ sources and sinks

- Plant activity
- Organics → CO₂
- Soil carbonate
- Soil moisture
- Weather and seasons

Produce CO₂

Consume CO₂

False positives
- Mask signal

False negatives
- Dampen signal
Background Measurements

- Many methods require background measurements.
- Measure “background” CO₂ for at least 1 year before project start to understand seasonal variability.
- Monitor CO₂ during project and compare to background.
- Significant increase from background during a project could signal a leak.
Drawbacks To Background Measurements

- Natural CO$_2$ variability can mask a moderate leakage signal
- One year of background characterization might not account for CO$_2$ variability from climate, land use, and ecosystem variations during a project (tens to hundreds of years)
- Requires long lead time
- Background CO$_2$ cannot be measured across all potential leak points
Complex migration pathways and transport mechanisms
Approach: Where To Look?

• **Sampling Grids**
  – Good spatial coverage
  – Expensive and time consuming
  – Still doesn’t cover all area
  – Can get similar results with remote sensing methods.

• **Targeted**
  – Heavily based on risk
  – Small spatial coverage
  – More economic than grids
  – Less likely to find a leak
Available Monitoring Tools

<table>
<thead>
<tr>
<th>Description, Benefits Challenges</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 subsurface</td>
</tr>
<tr>
<td>12 near-surface</td>
</tr>
<tr>
<td>5 atmospheric</td>
</tr>
</tbody>
</table>

### Table 2-1: Comprehensive List of Proposed Monitoring Methods Available for GS Projects

<table>
<thead>
<tr>
<th>Monitoring Technique</th>
<th>Description, Benefits, and Challenges</th>
</tr>
</thead>
</table>
| **CO₂ Detectors**    | *Description:* Sensors for monitoring CO₂ either intermittently or continuously in air.  
*Benefits:* Relatively inexpensive and portable. Mature and new technologies represented.  
*Challenges:* Detect leakage above ambient CO₂ emissions (signal to noise). |
| **Eddy Covariance**  | *Description:* Atmospheric flux measurement technique to measure atmospheric CO₂ concentrations at a height above the ground surface.  
*Benefits:* Mature technology that can provide accurate data under continuous operation.  
*Challenges:* Very specialized equipment and robust data processing required. Signal to noise. |
| **Advanced Leak Detection System** | *Description:* A sensitive three-gas detector (CH₄, Total HC, and CO₂) with a GPS mapping system carried by aircraft or terrestrial vehicles.  
*Benefits:* Good for quantification of CO₂ fluxes from the soil.  
*Challenges:* Null result if no CO₂. |
| **Laser Systems and LIDAR** | *Description:* Open-path device that uses a laser to shine a beam – with a wavelength that CO₂ absorbs – over many meters.  
*Benefits:* Highly accurate technique with large spatial range. Non-intrusive method of data collection over a large area in a short timeframe.  
*Challenges:* Needs favorable weather conditions. Interference from vegetation, requires time laps Signal to noise. |
| **Tracers (Isotopes)** | *Description:* Natural isotopic composition and/or compounds injected into the target formation along with the CO₂.  
*Benefits:* Used to determine the flow direction and early leak detection.  
*Challenges:* Samples need analyzed offsite of project team does not have the proper analytical equipment. |

*See Appendix I for Details*
# Near-Surface Methods

<table>
<thead>
<tr>
<th>Monitoring Technique</th>
<th>Description, Benefits, and Challenges</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ecosystem Stress Monitoring</td>
<td><strong>Description:</strong> Satellite or airplane-based optical method. <strong>Benefits:</strong> Easy and effective reconnaissance method. <strong>Challenges:</strong> Detection only after emission has occurred. Quantification of leakage rates difficult. Changes not related to CCS lead to false positives. Not all ecosystems equally sensitive to CO₂.</td>
</tr>
<tr>
<td>Tracers</td>
<td><strong>Description:</strong> CO₂ soluble compounds injected along with the CO₂ into the target formation. <strong>Benefits:</strong> Used to determine the hydrologic properties, flow direction and low-mass leak detection. <strong>Challenges:</strong> Many of the tested CO₂ soluble tracers are GHGs, and therefore, add to risk profile.</td>
</tr>
<tr>
<td>Groundwater Monitoring</td>
<td><strong>Description:</strong> Sampling of water or vadose zone/soil (near surface) for basic chemical analysis. <strong>Benefits:</strong> Mature technology, easier detection than atmospheric. Early detection prior to large emissions. <strong>Challenges:</strong> Significant effort for null result (no CO₂ leakage). Relatively late detection of leakage.</td>
</tr>
<tr>
<td>Thermal Hyperspectral Imaging</td>
<td><strong>Description:</strong> An aerial remote sensing approach primarily for enhanced coalbed methane recovery and sequestration. <strong>Benefits:</strong> Covers large areas; detects CO₂ and CH₄. <strong>Challenges:</strong> Not a great deal of experience with this technique in GS.</td>
</tr>
<tr>
<td>Synthetic Aperture Radar (SAR &amp; InSAR)</td>
<td><strong>Description:</strong> A satellite-based technology in which radar waves are sent to the ground to detect surface deformation. <strong>Benefits:</strong> Large-scale monitoring (100 km × 100 km). <strong>Challenges:</strong> Best used in environments with minimal topography, minimal vegetation, and minimal flow. Only useful in time-lapse.</td>
</tr>
<tr>
<td>Color Infrared (CIR) Transparency Films</td>
<td><strong>Description:</strong> A vegetative stress technology deployed on satellites or aerially. <strong>Benefits:</strong> Good indicator of vegetative health, which can be an indicator of CO₂ or brine leakage. <strong>Challenges:</strong> Detection only post-leakage. Need for deployment mechanism (i.e., aircraft).</td>
</tr>
<tr>
<td>Tiltmeter</td>
<td><strong>Description:</strong> Measures small changes in elevation via mapping tilted, either on the surface or in subsurface. <strong>Benefits:</strong> Mature oil field technology for monitoring stream or water injection, CO₂ flooding and hydrofracturing. <strong>Challenges:</strong> Access to surface and subsurface. Measurements are typically collected remotely.</td>
</tr>
<tr>
<td>Flux Accumulation Chamber</td>
<td><strong>Description:</strong> Quantifies the CO₂ flux from the soil, but only from a small, predetermined area. <strong>Benefits:</strong> Technology that can quickly and effectively determine CO₂ fluxes from the soil at a predetermined area. <strong>Challenges:</strong> Only provides instantaneous measurements in a limited area.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Monitoring Technique</th>
<th>Description, Benefits, and Challenges</th>
</tr>
</thead>
<tbody>
<tr>
<td>Induced Polarization</td>
<td><strong>Description:</strong> Geophysical imaging technology commonly used in conjunction with DC resistivity to distinguish metallic minerals and conductive aquifers from clay minerals in subsurface materials. <strong>Benefits:</strong> Detecting metallic materials in the subsurface with fair ability to distinguish between different types of mineralization. Also a useful technique in clays. <strong>Challenges:</strong> Does not accurately depict non-metallic based materials. Typically only used for characterization.</td>
</tr>
<tr>
<td>Spontaneous (Self) Potential</td>
<td><strong>Description:</strong> Measurement of natural potential differences resulting from electrochemical reactions in the subsurface. Typically used in groundwater investigations in geotechnical engineering applications for seepage studies. <strong>Benefits:</strong> Fast and inexpensive method for detecting metal in the near subsurface. Useful in rapid reconnaissance for base metal deposits when used in tandem with EM and geochimical techniques. <strong>Challenges:</strong> Should be used in conjunction with other technologies. Qualitative only.</td>
</tr>
<tr>
<td>Soil and Vadose Zone Gas Monitoring</td>
<td><strong>Description:</strong> Sampling of gas in vadose zone/soil (near surface) for CO₂. <strong>Benefits:</strong> CO₂ retained in soil porosity provides a longer residence time. Detection of elevated CO₂ concentrations well above background levels provides indication of leak and migration from the target reservoir. <strong>Challenges:</strong> Significant effort for null result (no CO₂ leakage). Relatively late detection of leakage.</td>
</tr>
<tr>
<td>Shallow 2-D Seismic</td>
<td><strong>Description:</strong> Closely spaced geophones along a 2-D seismic line. <strong>Benefits:</strong> Mature technology that can provide high resolution images of the presence of gas phase CO₂. Can be used to locate “bright spots” that might indicate gas, also used in time-lapse. <strong>Challenges:</strong> Semi-quantitative. Cannot be used for mass-balance CO₂ dissolved or trapped or mineral not monitored. Out of plane migration not monitored.</td>
</tr>
</tbody>
</table>
ZERT Controlled Release Site

- Zero Emissions Research and Technology Center
- Montana State University, Bozeman
- Controlled CO$_2$ release
- Leakage scenario for near surface monitoring research
- 98 m long horizontal pipe
- 2 meters below surface in groundwater
- 6 zones of CO$_2$ release

Spangler et al., 2009 Energy Procedia,
Monitoring Tools Tested At ZERT

- CO$_2$ flux chambers
- Eddy covariance
- Tracers
- Shallow geophysical

- LIDAR
- Soil gas geochemistry
- Water chemistry
- Plant stress
LIDAR (Light Detection and Ranging)

- Optical remote sensing technology using light (sometimes generated by a laser)
- Can determine CO₂ concentrations or detect plant stress.
- Can indicate plant stress before it is visible to the eye.

Male et al., Environ Earth Science (2010)
Eddy Covariance

- Uses statistical analysis of atmospheric data to calculate vertical turbulent fluxes.
- Complex, uses many assumptions, much data
- Proven technology in atmospheric monitoring
- At ZERT showed limits on detection sensitivity.
  - No detection of Release 1 (0.1 t CO\textsubscript{2}/day)
  - Detection of Release 2 (0.3 t CO\textsubscript{2}/day)

Figure 2. Average nighttime (open circles) and daytime (black dots) $F_c$ measured in (a) 2006 and (b) 2007. Vertical dashed lines and gray zones indicate timing of mowing and CO\textsubscript{2} releases, respectively.

Lewicki et al., Energy Procedia 1 (2009)
CO₂ flux chambers

- Measures the leakage of CO₂ to atmosphere
- Accurate
- Small measurement area so time intensive
- Flux does not always represent CO₂ concentrations in the soil
- Does not distinguish signal from noise without extensive background measurements

Fig. 10 Map of log soil CO₂ flux measured on 7/30/2008 using the accumulation chamber method. Point (0, 0) indicates the location of the reference grid origin. The black box in the center of the grid points shows the approximate location of the trace of the horizontal well on the ground surface.
Groundwater Chemistry

- Measures CO$_2$ input indirectly
  - Monitors the results of CO$_2$ input (mineral dissolution), not CO$_2$ itself
  - Tracers
    - Noble gases, stable isotopes
- Depends on aquifer sediments
- Measures brine directly
- Needs background
- At ZERT found fluctuating geochemistry
Introduced Tracers - PFT

- Perfluorocarbon Tracers (PFTs)
- Low natural background levels – (don’t need background measurements)
- Excellent detection limits
- Inert and stable
- Powerful greenhouse gases
- Many false positives
- Cannot quantify CO$_2$

Fig. 10. Contour plots representing soil–gas tracer concentrations at 1 m depth measured at the points marked by black dots. Colors display relative tracer concentration within each set with pinks and reds the highest, orange and yellow medium and green and blues are the lowest amounts of tracer.

Strazisar et al., 2009, International Journal of Greenhouse Gas Control
Shallow Geophysical

• Resistivity and electromagnetic induction survey
• Shows high permeability layers and migration pathways
• Can detect CO\textsubscript{2}

Resistivity/depth profiles acquired along an east/west line through the vertical injection well before (upper) and after (lower) CO\textsubscript{2} injection. Area made more conductive (less resistive) by the injection of CO\textsubscript{2} is depicted by dashed red line. Strazisar et al., 2009, International Journal of Greenhouse Gas Control
Soil Gas Geochemistry

- Two approaches
  - Concentration-based
    - Measure CO₂ in soils and compare to background
  - Process-based
    - Use ratios among major gases (CO₂, CH₄, N₂, O₂) to identify near surface processes
    - Successfully identified signal from noise at ZERT without using background measurements
    - Can potentially quantify a leak
    - Still a very new method

Romanak et al, 2012
Challenge: Proving A Negative

Example:
SACROC Oilfield, West Texas

- 40 years CO$_2$ injection for enhanced oil recovery
- 150 Mt CO$_2$ injected
- 75 Mt recovered and recycled
- No indication of impact to groundwater quality

Where is the rest?
Real Example: Allegation of a Leak near the Weyburn-Midale Monitoring and Storage Project Saskatchewan Canada
IEAGHG Weyburn-Midale Monitoring and Storage Project

• First large scale monitoring project (2000-2011)
• EOR operated by Cenovus Energy
• Managed by Petroleum Technology Research Centre (PTRC)
• Since 2000 > 16 M tonnes of CO₂ injected
• Extensive near-surface monitoring research program

Weyburn Soil Gas Monitoring

Research Objectives

• Define baseline
• Detect gas migration pathways
  - targeted
  - grid (14 km$^2$, 200 m spacing)
• Assess near-surface monitoring methods

Weyburn soil-gas grid: (Riding and Rochelle, 2009).
Kerr Allegation

- **July 2003**: Kerrs excavated gravel pits. CO$_2$ injection began in the vicinity of the property.
- **July 2004**: Kerrs allegedly began observing various unusual disturbances in ponds, water wells and soils on the property.
- **August 2010/ Feb 2011**: Petro-Find Geochem Ltd conducted geochemical assessments of the Kerr property. Found soil gas anomaly of $\sim 10\%$ CO$_2$. 
Petro-Find Conclusion

“...source of the high concentrations of CO₂ in soils of the Kerr property is clearly the anthropogenic CO₂ injected into the Weyburn reservoir.”

Site investigation of SW30-5-13-W2M
Petro-Find Geochem Ltd (2010)
Media Attention

January 11, 2010

**THE GLOBE AND MAIL**

Carbon capture leak forces Saskatchewan couple to leave farm

Published Tuesday, Jan. 11, 2011 6:12PM EST

Pair abandon Saskatchewan farm because of blowouts, dead animals and algae

---

**CBC news**

CO2 leaks worry Sask. farm

Last Updated: Tuesday, January 11, 2011 | 8:40 PM ET

The Canadian Press

A Saskatchewan greenhouse gas storage site could be storing carbon dioxide leaking out, killing groundwater, foaming to the surface like shaken-up soda pop.

Cameron and Jane Kerr, who own land above the Weyburn oilfield in eastern Saskatchewan, have released a consultant's report that claims to link high concentrations of carbon dioxide in their soil to gas injected underground.
Petroleum Technology Research Centre Response

“Researchers, engineers, geologists and geophysicists involved in the Weyburn project have reviewed the Petro-Find report and concluded that it does not support its claim.”

PTRC Response to Petro-Find report
www.ptrc.ca
Why the Confusion?

• Vadose zone CO₂ is naturally variable
• Injected (anthropogenic) CO₂ is isotopically similar to natural CO₂
• Comparison with background data imprecise
  – Kerr Farm not in Weyburn monitoring areas
Two Kerr Farm Investigations

- **Dissolved Gas in Groundwater**
  - $^{14}\text{C}$ and $^{13}\text{C}$ isotope tracers

- **Soil gas measurements**
  - Grid sampling (~ 70 points)
  - Mix of background comparison and some processed-based
  - $^{14}\text{C}$ and $^{13}\text{C}$ isotope tracers
  - 3 samplings
  - 2 at a background site, 1 at the Kerr Farm

- **Dissolved Gas in Groundwater**
  - Noble gas tracer

- **Soil gas measurements**
  - Targeted sampling (~ 20 points)
  - 100% processed-based
  - 1 sampling at Kerr Farm (no background)
Lessons From Kerr Farm Incident

Different studies,
Different approaches
Different tools

Same conclusion
NO LEAK!

Need protocol for incidence response that is:

- Effective
- Economical
- Efficient
- High level of certainty
Summary of Near Surface Monitoring

- Near-surface monitoring is for assurance; including leak detection, assessing environmental impacts, quantifying leakage, and addressing public concerns.
- The biggest challenge is separating leakage signal from background noise.
- Most approaches require at least one year of background monitoring.
- Background monitoring may not capture full variability over the life of a project, requires a lead time, and cannot be done everywhere within a project's boundaries.
Summary of Near Surface Monitoring

• In some ways, monitoring attempts to prove a negative
• There are many tools and approaches that can be used. All have benefits and challenges. A site specific combination of approaches may be required.
• There is a need for integrated, cost effective, efficient, economical monitoring plans for industry.
Contact Information

Katherine Romanak
Gulf Coast Carbon Center
Bureau of Economic Geology
The University of Texas at Austin

katherine.romanak@beg.utexas.edu

http://www.beg.utexas.edu/gccc/

http://www.storeco2now.com/