Near-Surface Monitoring at Geologic CO₂ Storage Sites

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One Geologist’s Story
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

Nicot et. al, 2008, GCCC Digital Publication Series #08-03g
Developing a Monitoring Plan

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

[Image of monitoring equipment and data visualization]

courtesy of Becky Smyth
Deep versus Near-Surface Monitoring

- **Near-Surface Monitoring Zone**
  - Biosphere
  - Vadose zone
  - Shallow groundwater
  - Seal
  - Above Zone Interval
  - Static, quiet environment, variability is from CO$_2$ injection, CO$_2$/brine migration
  - 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**
  - CO$_2$ plume
  - Reservoir

*Figure courtesy of Sue Hovorka*
Near-Surface Monitoring

**ADVANTAGES**
- Inexpensive and accessible
- Monitors area near “release to atmosphere”
- Direct observation of resources
  - Groundwater
  - Biosphere
- Aids in assessing impacts to the environment
- Useful for responding to public concerns
- Important for quantification/accounting

**CHALLENGES**
- Locating an anomaly
  - Need wide coverage over large areas
- Attributing source of anomaly
  - natural variation
  - leakage
Where To Look?

• **Sampling Grids**
  – Good spatial coverage
  – Expensive and time consuming
  – Still doesn’t cover all area

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

• **Remote Sensing**
  – Excellent spatial coverage
  – No land access issues.
  – Interferences/vegetation
Near-Surface Leakage Assessment

1. Locate Anomaly
2. Attribute Source
3. Generated In-situ
   - Exogenous
   - Determine the origin
4. No Leakage
5. Reservoir
6. Intermediate Zone
   - No Leakage

Leakage Migration Mechanism
Leakage Flux
No Leakage
Attribution: Signal over Noise

Natural CO$_2$ sources and sinks
- Plant activity
- Organics $\rightarrow$ CO$_2$
- Soil carbonate
- Soil moisture
- Weather and seasons

Background “noise”

Leak Signal

Leak

Produce CO$_2$

Consume CO$_2$

False positives
- Mimic signal

False negatives
- Dampen signal
Popular Methods

Background Measurements

• Measure “background” CO\textsubscript{2} for 1-3 years before project start to understand seasonal variability.
• Monitor CO\textsubscript{2} during project and compare to background.
• Significant increase from background during a project could signal a leak

Isotopes

• Different isotopic signatures can indicate the source of CO\textsubscript{2} whether natural or injected.
Popular Methods - Challenges

Background Measurements

- Natural CO₂ variability can mask a moderate leakage signal
- Requires long lead time
- “Baseline” will be dynamic
  - climate, land use, and ecosystem variations during a project
- Background CO₂ cannot be measured across all potential leak points

Isotopes

- Not always definitive
Complex migration pathways and transport mechanisms
Available Monitoring Tools

Description, Benefits, Challenges

20 subsurface
12 near-surface
5 atmospheric

### Atmospheric Monitoring Techniques

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

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

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<td>Induced Polarization</td>
<td>Description: Geophysical imaging technology commonly used in conjunction with DC resistivity to distinguish metallic minerals and conductive aquifers from clay minerals in subsurface materials.</td>
<td>Detecting metallic materials in the subsurface with fair ability to distinguish between different types of mineralization. Also a useful technique in clays.</td>
<td>Does not accurately depict non-metallic based materials. Typically only used for characterization.</td>
</tr>
<tr>
<td>Spontaneous (Self) Potential</td>
<td>Description: Measurement of natural potential differences resulting from electrochemical reactions in the subsurface. Typically used in groundwater investigations and in geotechnical engineering applications for seismic studies.</td>
<td>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 geophysical techniques.</td>
<td>Should be used in conjunction with other technologies. Qualitative only.</td>
</tr>
<tr>
<td>Soil and Vadose Zone Gas Monitoring</td>
<td>Description: Sampling of gas in vadose zone/soil (near surface) for CO₂.</td>
<td>CO₂ retained in soil gases provides a longer residence time. Detection of elevated CO₂ concentrations well above background levels provides indication of leak and migration from the target reservoir.</td>
<td>Significant effort for null result (no CO₂ leakage). Relatively late detection of leakage.</td>
</tr>
<tr>
<td>Shallow 2-D Seismic</td>
<td>Description: Closely spaced geophones along a 2-D seismic line.</td>
<td>More technology that can provide high resolution images of the presence of gas phase CO₂. Can be used to locate &quot;bright spots&quot; that might indicate gas, also used in time-laps.</td>
<td>Semi-quantitative. Cannot be used for mass balance CO₂ dissolved or trapped as 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

- CO₂ 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 CO$_2$ 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$_2$/day)
  - Detection of Release 2 (0.3 t CO$_2$/day)

Figure 2. Average nighttime (open circles) and daytime (black dots) $F_z$ measured in (a) 2006 and (b) 2007. Vertical dashed lines and gray zones indicate timing of moving and CO$_2$ releases, respectively.

Lewicki et al., Energy Procedia 1 (2009)
CO$_2$ Flux Chambers

- Measures the leakage of CO$_2$ to atmosphere
- Accurate
- Small measurement area so time intensive
- Flux does not always represent CO$_2$ concentrations in the soil
- Does not distinguish signal from noise without extensive background measurements
Groundwater Chemistry

• Measures CO$_2$ input indirectly
  – Results of CO$_2$ input (e.g. 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
- Assumed 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$_2$

Resistivity/depth profiles acquired along an east/west line through the vertical injection well before (upper) and after (lower) CO$_2$ injection. Area made more conductive (less resistive) by the injection of CO$_2$ is depicted by dashed red line. Strazisar et al., 2009, International Journal of Greenhouse Gas Control.
Soil GasGeochemistry

• Two approaches
  – Concentration-based
    • Measure CO$_2$ in soils and compare to background
  – Process-based
    • Use ratios among major gases (CO$_2$, CH$_4$, N$_2$, O$_2$) 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 CO₂ injection for enhanced oil recovery
- 150 Mt CO₂ 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 CO$_2$ Monitoring and Storage Project

- Largest geologic CO$_2$ monitoring and storage project
- Since 2000 > 24 M tonnes of CO$_2$ injected
- CO$_2$-EOR operated by Cenovus Energy
- Studied by an international team of CO$_2$ storage experts
- Managed by Petroleum Technology Research Centre (PTRC)

News of a “Leak” at the Kerr Farm
January 11, 2011

Land fizzing like soda pop: farmer says CO2 injected underground is leaking

By: Bob Weber and Jennifer Graham, The Canadian Press
Postmed: 01/11/2011 10:22 AM | Comments: 9

Carbon injected underground is leaking: Sask. farmers

Study Region

CO2 Levels at Leaking Canadian Carbon Storage Project Could Asphyxiate You in One Place

Pfft Goes Promise Of Pumping CO2 Underground
Alleged Land Disturbances
Petro-Find Conclusion

“The...source of the high concentrations of CO$_2$ in soils of the Kerr property is clearly the anthropogenic CO$_2$ injected into the Weyburn reservoir.”

Petroleum Technology Research Centre Response

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

PTRC Response to Petro-Find report
Why the Confusion?

- Vadose zone CO$_2$ is naturally variable
- Injected (anthropogenic) CO$_2$ is isotopically similar to natural CO$_2$
- Comparison with background data imprecise
  - Kerr Farm not in Weyburn monitoring areas
Investigations in Response to Allegation

European Research Team

The Operator

Third Party
Investigations in Response to Allegation

CONCLUSION: NO LEAKAGE
Validating the Allegation

- PetroFind study used as reconnaissance survey
- Targeted approach
  - 10 sampling locations
  - Minimal number of analytes
  - Process-based soil gas method
CO₂ is from biologic respiration with some dissolution of CO₂ into groundwater. No input of exogenous gas from depth.

Methane oxidation is negligible.
Lessons From Kerr Farm Incident

Different studies,
Different approaches
Different tools

Need protocol for allegation response that is:

- Effective
- Economical
- Efficient

Same conclusion
NO LEAK!

- 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

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

http://www.storeco2now.com/