Assessing the long term efficacy of CO$_2$ geological storage by atmospheric monitoring

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The need to monitor the atmosphere

• Verify the containment of CO$_2$ storage
• The atmosphere is where CO$_2$
  - causes greenhouse climate change
  - can impact on health and safety
• Complement subsurface monitoring

correspondence

Nature 433, 683 (17 February 2005); doi:10.1038/433683b

Emissions control needs atmospheric verification

E. Nisbet, 2005
Attributes of atmospheric monitoring

• Continuous, unattended
• Not invasive
• Integrates across multiple point or diffuse emissions
• But is it too late if a leak is detected?
## Atmospheric M and V hierarchy

<table>
<thead>
<tr>
<th>Aim</th>
<th>Concern/purpose</th>
<th>Atmospheric quantities required</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detect leak</td>
<td>Air quality, HS and E, public acceptance, inform project operators</td>
<td>CO₂ concentrations</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Other gas concentrations, isotopes, tracers</td>
</tr>
<tr>
<td>Attribute leak</td>
<td>Regulatory matters, public acceptance, inform project operators</td>
<td>Transport and dispersion - CO₂ fluxes</td>
</tr>
<tr>
<td>Quantify leak</td>
<td>Effectiveness of GH gas control, carbon accounting and trading</td>
<td></td>
</tr>
</tbody>
</table>

* denotes the key quantities required for each aim.
What rate of leakage is acceptable?

- HS and E requirements
- GHG mitigation requirements
- Geological expectations

……..but estimates are always > zero
Global leak rate scenarios

Leakage rate
% per year

Leakage of 1% /yr provides short term mitigation
0.1% /yr or less is required for sustainability

Could this be verified by atmospheric techniques?
CO₂ (and associated gases) in the atmosphere—global baseline monitoring
Global CO$_2$, CH$_4$ and N$_2$O past 2000 years-
from Cape Grim baseline station (1978+) and Antarctic ice

Past decade - background atmosphere

Data: CSIRO Marine and Atmospheric Research and Bureau of Meteorology
CO$_2$ in the local atmosphere

Data: CSIRO Marine and Atmospheric Research and Bureau of Meteorology

CO$_2$ (ppm)

- CO$_2$ (Cape Grim)
- CO$_2$ (Cape Grim baseline)
- CO$_2$ (Aspendale)
- CO$_2$ (Tumbarumba)

422 ppm

CSIRO CO2 CRC
CO$_2$ and CH$_4$ in the rural atmosphere

Griffith, Leuning, Denmead, Jamie,
*Atmospheric Environment*, 2002
How to differentiate these variations from possible leaks

• Baseline record - before, during, after injection
• Tracers - added
• Tracers - natural
• Measure natural fluxes and determine residual
• Model natural fluxes and determine residual
• Statistical strategy based on different temporal characteristics
• Atmospheric transport- dispersion and back trajectories
“Tracers” to discriminate CO$_2$ storage leak from:

<table>
<thead>
<tr>
<th>Source</th>
<th>Naturally occurring</th>
<th>Introduced with fluid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Terrestrial biology</td>
<td>$^{13}$CO$_2$, $^{14}$CO$_2$</td>
<td>SF$_6$, CF$_4$</td>
</tr>
<tr>
<td>Biomass burning</td>
<td>CO</td>
<td>SF$_6$, CF$_4$</td>
</tr>
<tr>
<td>Fossil fuel burning</td>
<td>CO, $^{14}$CO$_2$</td>
<td>SF$_6$, CF$_4$</td>
</tr>
<tr>
<td>Livestock CH$_4$ cf displaced CH$_4$</td>
<td>$^{13}$CH$_4$, $^{14}$CH$_4$</td>
<td></td>
</tr>
<tr>
<td>Geological-natural</td>
<td>Radon?</td>
<td>SF$_6$, CF$_4$</td>
</tr>
<tr>
<td>Geological-facilities</td>
<td>?</td>
<td>SF$_6$, CF$_4$</td>
</tr>
</tbody>
</table>
Concentration measurements

Continuous, in situ, high precision CO₂, linked to network and international standards - LoFlo analyser system

Flask air sampling for isotopes, tracers, CH₄….measurements back in laboratories
Measured CO₂ variations and $\delta^{13}$CO₂ signature-
Otway site natural variations

$\delta^{13}$CO₂ = -26 ‰
biospheric exchange
(C3 plants)
Flux tower and flux chamber

Images: R. Leuning    Data: M. Meyer
CSIRO Marine and Atmospheric Research
An improved strategy to detect CO₂ leakage for verification of geologic carbon sequestration

J. L. Lewicki,¹ G. E. Hilley,² and C. M. Oldenburg¹

Received 2 August 2005; revised 26 August 2005; accepted 14 September 2005; published 15 October 2005.

[¹] The long-term storage of CO₂ must be verified to ensure the success of geologic carbon sequestration projects. To detect subtle CO₂ leakage signals, we present a strategy that integrates near-surface measurements of CO₂ fluxes or concentrations with an algorithm that enhances temporally- and spatially-correlated leakage signals while suppressing random background noise. We assess the performance of this strategy using synthetic CO₂ flux data sets and modeled surface CO₂ leakage. These simulations provide a means of estimating the number of measurements required to detect a potential CO₂ leakage signal of given magnitude and area. Results show that given a rigorous and well-planned field sampling program, subtle surface CO₂ leakage may be detected using the algorithm; however, leakage of very limited spatial extent or exceedingly small magnitude may be difficult to detect with a reasonable set of monitoring resources. Citation: Lewicki, J. L., G. E. Hilley, and C. M. Oldenburg (2005), An improved strategy to detect CO₂ leakage for verification of geologic carbon sequestration, Geophys. Res. Lett., 32, L19403, doi:10.1029/2005GL024281.

1. Introduction

[²] One strategy to mitigate potential climate change associated with elevated atmospheric CO₂ concentrations is the sequestration of anthropogenic CO₂ in deep geologic formations [e.g., International Energy Agency, 1997; et al., 2003], within which a potentially small CO₂ anomaly may be hidden.

[³] We present a strategy that integrates near-surface measurements of CO₂ with statistical analysis to enhance properties of the data that are associated with leakage, while reducing random background contributions. Using a suite of synthetic CO₂ flux data sets and modeled CO₂ surface leakage from a flow and transport simulator, we investigate various combinations of sampling and analysis approaches to optimize leakage detection and quantification while minimizing the number of measurements. We discuss implications for geologic carbon storage verification and other studies where detection of a small anomalous signal within background noise is required.

2. Methods

[⁴] Our filtering method exploits several contrasting properties of near-surface CO₂ fluxes and concentrations derived from natural background processes versus those from CO₂ leakage. First, the production of CO₂ by background processes (e.g., soil respiration) is highly spatially heterogeneous; realistic soil CO₂ fluxes and concentrations are therefore poorly correlated on moderate to large spatial scales (e.g., ≥5 m) [e.g., Steyn et al., 2000; Xu and Qi, 2001; Lewicki et al., 2003]. In contrast, CO₂ derived from leakage along a well bore or fault should be relatively
Take advantage of atmospheric transport

TAPM
(The Air Pollution Model, CSIRO)
Simulated plume for region of Barrow Island, NW Australia
Simulated concentration perturbations

CO$_2$ and tracers at Otway

700 m from point release at Otway site

1000 t CO$_2$/yr
(~1%/yr of Otway
0.01%/yr Gorgon)

TAPM simulation
using actual winds

SF$_6$ tracer introduced
at 1 micromolar

$^{14}$CO$_2$ based on natural occurrences, not introduced
Conclusions

• Verification of CO₂ storage by atmospheric monitoring will be appropriate for health and safety, public acceptance, carbon accounting and regulatory needs.

• Small leakage rates that would compromise storage are just detectable using a suite of techniques:
  - concentration measurements (continuous, precise)
  - tracer measurements (continuous, precise, natural and introduced compounds)
  - flux measurements
  – transport modelling

• Detection sensitivity will depend on the setting (meteorology, land cover, other sources), amount and type of CO₂ to be injected.