Monitoring Near-Surface Leakage During Controlled Releases of CO_2

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Abstract

The ZERT CO_2 release facility, located in an agricultural field in Bozeman, MT USA provides the opportunity to test field methods to detect, locate, and quantify potential CO_2 leakage from geologic carbon sequestration sites. CO_2 was released at varying rates (0.1 to 0.3 t d^{-1}) from a ~100 m long, ~2.5 m deep horizontal well in 2007 to 2009 and the resulting CO_2 leakage signals were monitored by numerous scientific institutions using a broad range of measurement technologies. Here, we show examples of monitoring of CO_2 leakage associated with a CO_2 release (0.3 t d^{-1}) that was carried out for one month during Summer 2008. We measured soil CO_2 fluxes using the accumulation chamber method on a grid repeatedly on a daily basis. Infrared sensors installed at 30 cm depth in the soil at 0, 2.5, 5, 7.5 and 10 m NW of the well and at 4 cm above the ground surface at 0 and 5 m from the well continuously measured soil and atmospheric CO_2 concentrations. Net CO_2 fluxes were continuously measured by the eddy covariance method. Environmental parameters were concurrently monitored. Soil CO_2 fluxes and concentrations and atmospheric CO_2 concentrations recorded surface breakthrough, time to steady state, and post-release decline of the leakage signal. Soil CO_2 fluxes characterized the spatio-temporal evolution of the surface CO_2 flux leakage signal and quantified the leakage rate. Eddy covariance net CO_2 fluxes detected, while a least-squares inversion of CO_2 fluxes and corresponding footprint functions mapped and quantified, the surface CO_2 flux leakage signal.

I. CO_2 Release Well

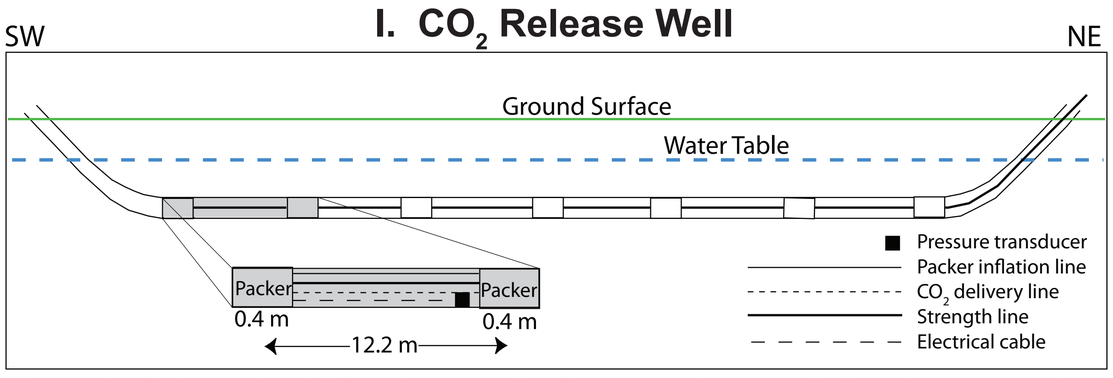
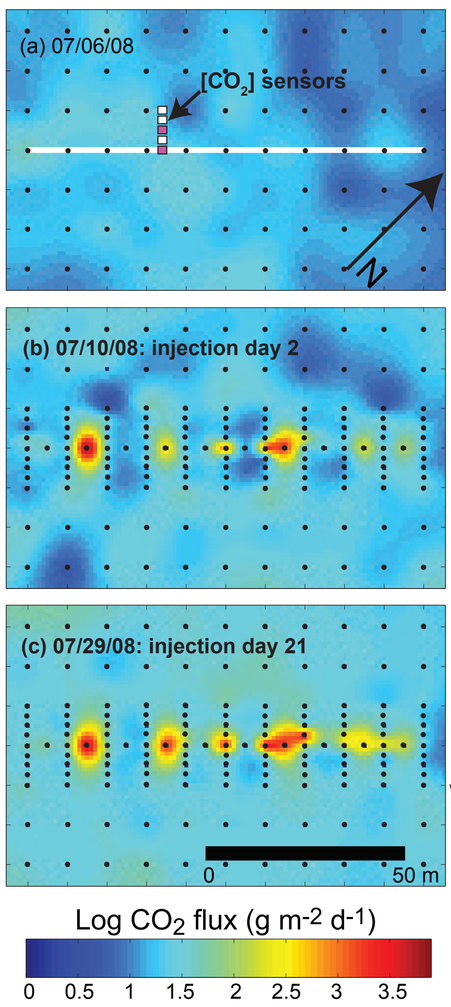


Figure 1. Schematic of CO_2 release well. Gray zone is expanded to show example of perforated well zone bounded by inflatable packers.

II. Accumulation Chamber Soil CO_2 Fluxes



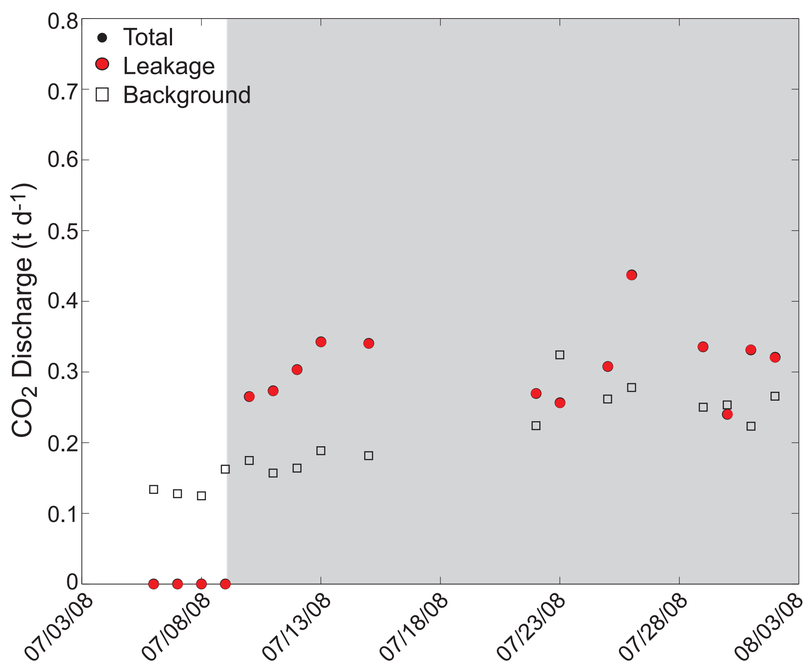


Figure 3. Total, background, and leakage CO_2 discharge (t d^{-1}) estimated based on daily grid chamber measurements of soil CO_2 flux (Figure 2). Grey zone shows timing of release.

Figure 2. Examples of maps of log soil CO_2 flux interpolated based on measurements made at black dots. White line, white squares, and magenta squares on (a) show locations of well trace, soil [CO_2] sensors, and soil and atmospheric [CO_2] sensors, respectively.

III. Atmospheric and Soil CO_2 Concentrations

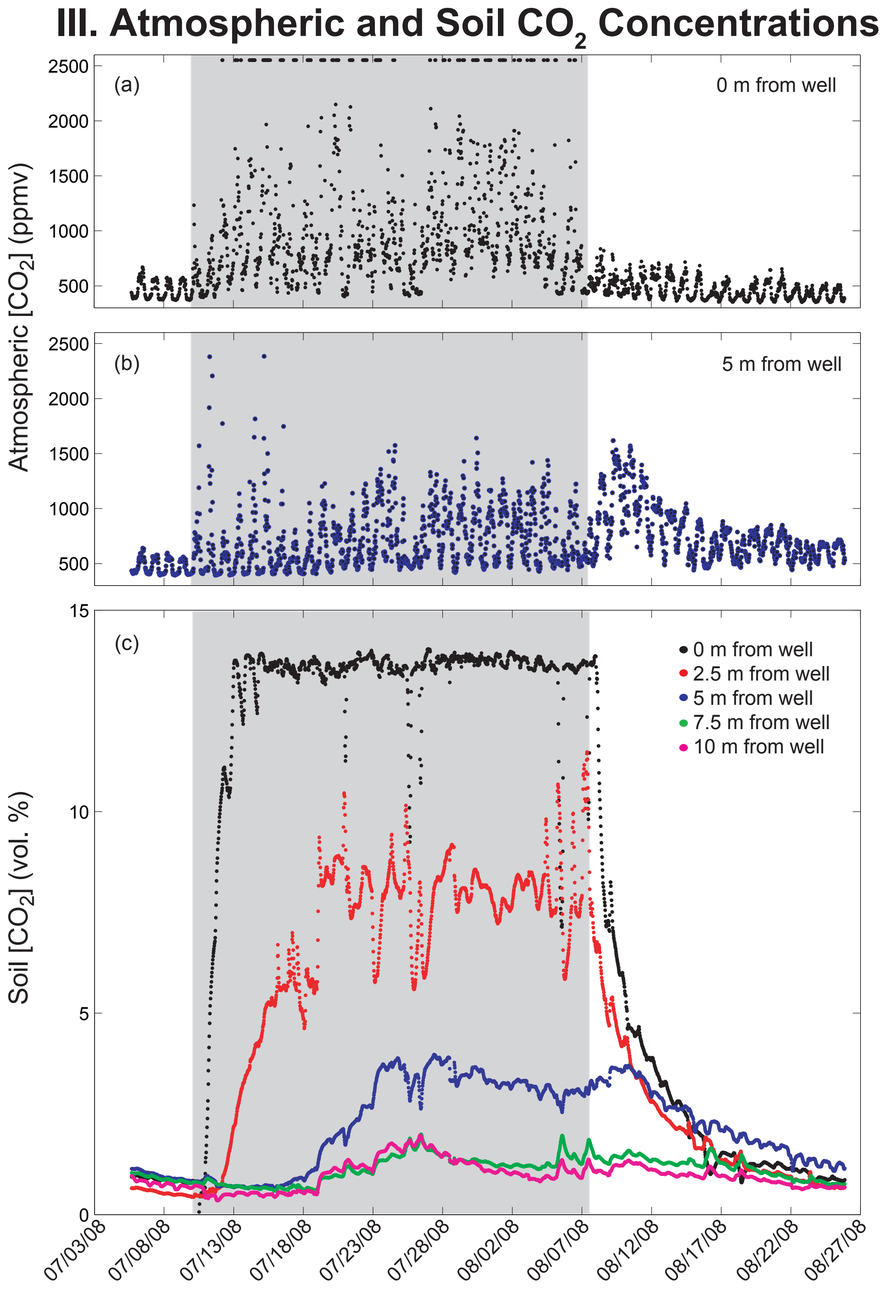


Figure 4. Atmospheric [CO_2] measured by sensors 4 cm above ground (a) 0 m and (b) 5 m from well (Figure 2a). (c) Soil [CO_2] measured at 30 cm depth by sensors at 0, 2.5, 5, 7.5, and 10 m from well. Grey zones show timing of release.

IV. Eddy Covariance Net CO_2 Fluxes

Calculated as the temporal covariance of vertical wind velocity (w) and atmospheric CO_2 density (c):

$$F_c = \overline{w'c'}$$

Fluxes arising from the release (F_{cr}) isolated by subtracting fluxes corresponding to a model for net ecosystem exchange (NEE) from F_c, where

$$NEE = -\left(\frac{F_{\max}\alpha PAR}{\alpha PAR + F_{\max}}\right) + R_{eco},$$

F_{max} = maximum CO_2 flux at infinite light
α = apparent quantum yield
PAR = measured photosynthetically active radiation
R_{eco} = ecosystem respiration, estimated as average nighttime F_c measured before and after release

The footprint function, $f(x_m - x', y_m - y', z_m - z_0)$, describes the relationship between F_{cr} measured at point (x_m, y_m, z_m) and the distribution of source CO_2 fluxes at the surface ($Q_{cr}(x', y', z' = z_0)$):

$$F_{cr}(x_m, y_m, z_m) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} Q_{cr}(x', y', z' = z_0) \cdot f(x_m - x', y_m - y', z_m - z_0)\,dx'dy'$$

If the spatial distribution of Q_{cr} is relatively constant over time, changes in F_{cr} will reveal this distribution as the footprint function varies with atmospheric conditions.

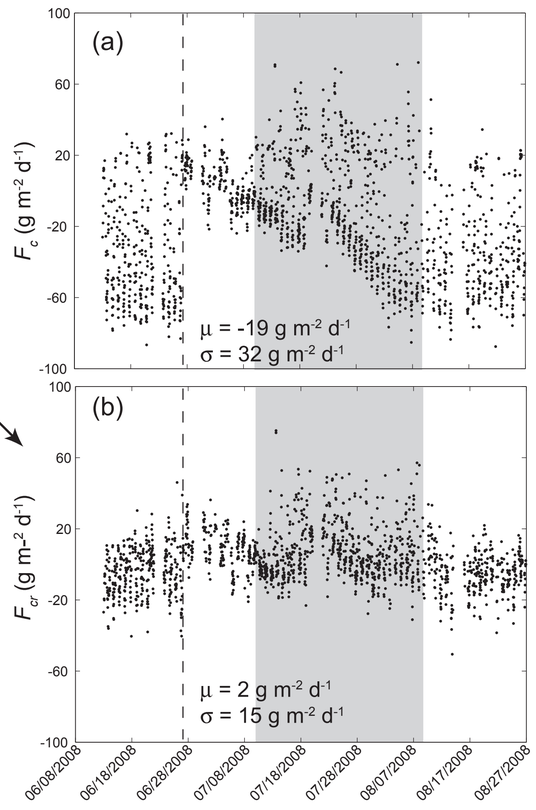


Figure 5. Time series of (a) F_c and (b) F_{cr}. Dashed lines and gray zones show timing of mowing of the field and CO_2 release.

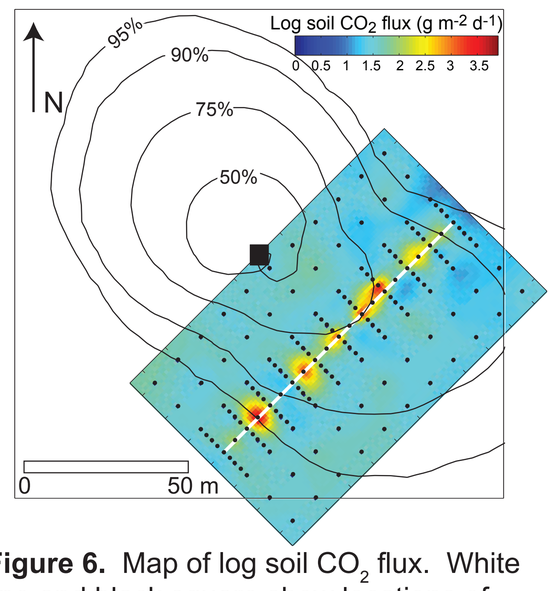


Figure 6. Map of log soil CO_2 flux. White line and black square show locations of surface trace of CO_2 release well and EC station, respectively. Mean eddy covariance flux 50, 75, 90, and 95% source area isopleths are shown for the CO_2 release time.

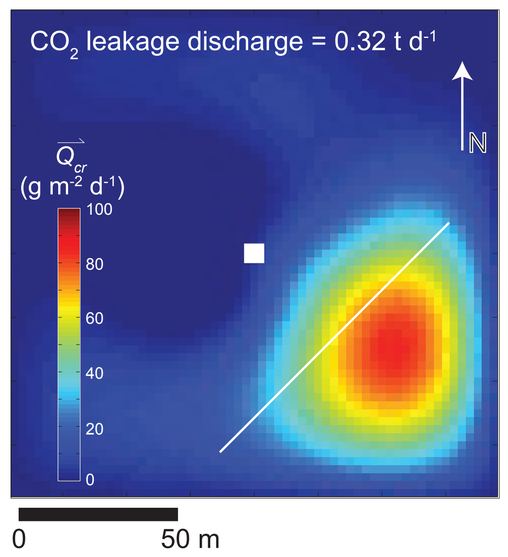


Figure 7. Map of surface CO_2 flux (Q_{cr}), modeled based on least-suqares inversion of 611 measured CO_2 fluxes and modeled footprint functions during the release time. White line and square show locations of surface trace of CO_2 release well and eddy covariance station, respectively.

V. Summary

1) Soil CO_2 flux and soil and atmospheric [CO_2] measurements characterized the surface breakthrough, spatio-temporal evolution, and post-release decline of the leakage signal associated with a controlled CO_2 release.
2) Soil CO_2 flux measurements quantified the leakage rate over time and showed that most injected CO_2 was emitted at the surface.
3) Variations in soil [CO_2] were modulated at 0-5 m sensors at low (<0.5 cycle d^{-1}) and high (>4 cycle d^{-1}) frequency by changes in injection rate and at all sensors at moderate(1-2 cycle d^{-1}) frequency by changes in atmospheric pressure, soil temperature and moisture, and wind speed.
4) Anomalously high atmospheric [CO_2] at 0 and 5 m sensors was observed a few hours after the release start and ~1 and 7 days prior to elevated soil [CO_2] at 0 and 5 m soil sensors, respectively, suggesting flow of leakage CO_2 along ground surface.
5) Removal of background ecosystem (NEE) from eddy covariance CO_2 fluxes enhanced the surface CO_2 leakage signal.
6) A least-squares inversion of 611 F_{cr} and corresponding modeled footprint functions recovered the location, length, and magnitude of the surface CO_2 flux leakage signal, although high wavenumber details of the signal were poorly resolved. The estimated total surface CO_2 leakage rate was within 7% of the release rate.

References

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