LEAKAGE AND SEEPAGE IN THE NEAR-SURFACE ENVIRONMENT: AN INTEGRATED APPROACH TO MONITORING AND DETECTION

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Abstract

Monitoring and detection of leakage and seepage of carbon dioxide (CO_2) in the near-surface environment is needed to ensure the safety and effectiveness of geologic carbon sequestration. Large leakage fluxes, e.g., through leaking wells, will be easier to detect and monitor than slow and diffuse leakage and seepage. The challenge of detecting slow leakage and seepage is discerning a leakage or seepage signal from within the natural background variations in CO_2 concentration and flux that are controlled by a variety of coupled processes in soil. Although there are no direct examples of leaking geologic carbon sequestration sites on which to base a proposed verification approach, we have been guided by our prior simulation studies of CO_2 leakage and seepage, which showed that large CO_2 concentrations can develop in the shallow subsurface even for relatively small CO_2 leakage fluxes. A variety of monitoring technologies exists for measuring CO_2 concentration and flux, but there is a gap between instrument performance and the detection of a leakage or seepage signal from within large natural background variability. We propose an integrated approach to monitoring and verification. The first part of our proposed approach is to characterize and understand the natural ecosystem before CO_2 injection occurs so that future anomalies can be recognized. Measurements of natural CO_2 fluxes using accumulation chamber (AC) and eddy correlation (EC) approaches, soil CO_2 concentration profiles with depth, and carbon isotope compositions of CO_2 are needed to characterize the natural state of the system prior to CO_2 injection. From this information, modeling needs to be carried out to enhance understanding of carbon sources and sinks so that anomalies can be recognized and subject to closer scrutiny as potential leakage or seepage signals. Long-term monitoring using AC, EC, and soil-gas analyses along with ecosystem and flow and transport modeling should continue after CO_2 injection. The integrated use of multiple measurements and modeling offers a promising approach to discerning and quantifying a small CO_2 leakage or seepage signal from within the expected background variability.

Introduction

One of the outstanding challenges of geologic carbon sequestration is verification, that is, ensuring that carbon dioxide (CO_2) is not leaking from the intended sequestration formation and seeping out of the ground. The most straightforward way of verifying CO_2 sequestration would seem to be direct monitoring and detection of anomalous CO_2 in the near-surface environment. While catastrophic releases to the atmosphere, such as through well blowouts, will be obvious failures and therefore present no challenge for detection, slow or diffuse leakage and seepage of CO_2 will be much more difficult to detect, monitor, and quantify. The difficulty of observing and quantifying diffuse CO_2 leakage and seepage arises because there are large spatial and temporal changes in CO_2 concentration and flux in natural ecosystems, making the main challenge the detection of a CO_2 leakage or seepage signal from within the natural background variation. We have developed an approach for monitoring and verification that involves a variety of integrated measurements and modeling that could be used to discern a CO_2 leakage or seepage signal.

In this brief paper, we summarize our proposed approach for geologic carbon sequestration verification. This approach is guided by results of numerical simulations of CO_2 leakage and seepage that we have carried out over the last few years, and by our experience in monitoring natural systems. Next we review controls on natural CO_2 in the shallow subsurface, and the technologies used for detecting and monitoring CO_2 in the near-surface environment. Finally, we present our ideas for an integrated approach to CO_2 verification.

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Review of Simulated CO_2 Leakage and Seepage

In prior work, we carried out simulations of CO_2 leakage and seepage using T2CA, a recently developed extension of TOUGH2 [1] that models CO_2 migration and dispersion in the subsurface and atmospheric surface layer. Details of the methods used in T2CA can be found in Oldenburg and Unger [2,3]. Numerical simulations showed that CO_2 concentrations can build up to high levels in the vadose zone (~100% CO_2 in soil gas) even when the leakage occurs at a relatively small rate. The reason for this is that there are very few dissipative processes for leaking CO_2 in the vadose zone. Examples of dissipative processes are dissolution of CO_2 into vadose zone moisture, and barometric pumping. However, even for relatively slow leakage rates (e.g., ~10^4 kg yr^{-1}), these processes do not significantly attenuate CO_2 leakage in the vadose zone [2]. Although the shallow subsurface CO_2 concentrations can be high, the CO_2 seepage flux across the ground surface can be small as CO_2 emissions occur over a large area. Our simulation results for the atmospheric surface layer show that CO_2 concentrations are very low above the ground surface, due to wind and turbulence which dilute and disperse CO_2 [3]. As wind speed increases, the surface-layer concentrations diminish to small values above the background concentration of 370 ppmv [3]. These observations of the expected behavior of leaking and seeping CO_2 have led us to focus monitoring and verification on the shallow subsurface, where CO_2 concentrations will tend to be high, and the daily and seasonal variability will be diminished relative to the above-ground region.

Natural Background CO_2 Fluxes and Concentrations

Background CO_2 in soil is derived primarily from the atmosphere and respiration, i.e., biologically mediated oxidation of organic carbon. A diagram of soil CO_2 sources and exchanges is shown in Figure 1. As shown in Figure 1, background soil CO_2 fluxes and concentrations are dependent on exchange with the atmosphere, production from decay of organic matter such as leaf litter, uptake by plants, production by root respiration, deep degassing, release from groundwater due to depressurization, and production by oxidation of organic carbon in groundwater at the water table. These processes are dependent on temperature, moisture, soil aeration, biological activity, and other factors [4]. The CO_2 degassed by flowing deep groundwater can have its CO_2 source from shallower sources (e.g., respiration, atmospheric CO_2, or particulate organic carbon) encountered at shallower depths over the long groundwater migration pathway (e.g., [5]). In summary, many complex and interrelated processes are active in controlling the natural background variation of CO_2 concentration, flux, and isotopic composition, and these processes can vary on short (hourly) and much longer time scales.

Near-Surface Monitoring Technologies

A wide range of methods is available for monitoring and detection of CO_2 fluxes and concentrations [6,7]. The infrared gas analyzer (IRGA) is used to measure CO_2 concentrations and is based on the principle of light absorption in the near-infrared part of the spectrum, typically 4.26 μm. IRGA-based devices are inexpensive, portable, and can measure CO_2 over a wide range of concentrations. Promising new methods of CO_2 monitoring include light detection and range finding (LIDAR), and new approaches such as hyperspectral imaging of vegetative stress [8].

Two basic approaches exist for measuring CO_2 fluxes: (1) the accumulation chamber (AC), and (2) the eddy correlation (EC) approach. In the AC method, an open-bottomed chamber is placed directly on the soil surface or on a collar installed on the ground surface and the rate of soil-CO_2 accumulation is measured using an IRGA (Figure 2a). This approach provides a small-scale measurement of soil-CO_2 flux. The measurement is relatively quick and many such measurements can be made over a large area, with statistical approaches used to interpolate an overall aereal flux [7]. The EC method provides a spatially averaged flux by correlating CO_2 concentration measured at a fixed height above the ground using an IRGA with local meteorological variations at the same elevation (Figure 2b). After time-averaging of the local variations of concentration and vertical wind speed, an average flux over a given footprint is derived. The footprint area is a function of the instrument height above the ground surface and local wind velocity, and is on the order of 10–100 times the instrument height. The advantage of EC is that it provides a spatially averaged flux that includes plant and soil sources; the limitation is that it assumes a horizontal ground surface and uniform plant cover over the footprint [9].

Proposed Integrated Approach to Sequestration Verification

There is a wide gap between the performance capabilities of technological devices and their applicability for geologic carbon sequestration leakage or seepage monitoring, detection, and verification. The fundamental challenge for verification when leakage and seepage fluxes are small is discerning the CO_2 leakage or seepage signal from natural background variability. Because CO_2 leakage and seepage at the ground surface is expected be a very rare phenomenon, monitoring at CO_2 sequestration sites will typically record background natural variability of the ecological system. To meet the challenge of CO_2 sequestration verification, sophisticated procedures or new technologies may have to be developed. In this section, we discuss ways that the CO_2 leakage or seepage signal could be discerned and quantified from measurements made in the near-surface environment with existing conventional devices.

The approach we suggest is based on our experience in modeling and field measurements of CO_2 emissions [2,3,10]. Experience has shown that the subsurface, even at depths of less than a meter, is much less affected by surface environmental processes and the strong dispersion effects of surface-layer winds and barometric pressure changes. Therefore, we expect the changes in CO_2 concentration, flux, and isotopic composition to be most recognizable in the subsurface, and therefore we focus our attention on monitoring and detection in the shallow subsurface. A great deal of effort should be put into understanding the natural ecological system and its baseline properties prior to CO_2 injection so that future anomalies in CO_2 concentration and flux can be identified. Particular attention should be given to understanding the natural variability in areas where leakage or seepage may be expected, e.g., near faults or around wells. Modeling and analyses of expected ecological (e.g., [11]) and CO_2 transport dynamics (e.g., [1,2,3]) should be integrated with the measurements to develop a comprehensive understanding of the system with and without CO_2 leakage and seepage.

We propose a variety of measurements for CO_2 sequestration verification. First, bulk soil-gas composition can be analyzed as a function of depth (i.e., vertical soil-gas profiles). Increasing CO_2 concentrations with depth indicate a CO_2 source at depth. If the source is oxidative decay of organic matter, there should be an associated decrease in O_2 concentration, the absense of which may suggest a CO_2 leakage source. A more definitive way of distinguishing the source of carbon in CO_2 in soil is by isotopic analyses. The characteristic properties of gas composition profiles and isotopic signatures for different sources of CO_2 are summarized in Table 1. Both the stable ^{13}C and radiogenic ^{14}C vary depending on the source of CO_2. However, only the absence of ^{14}C coupled with high local CO_2 concentrations provide a strong indicator of a fossil-fuel origin of CO_2 consistent with leaking CO_2 from a sequestration site. The overlap in ^{13}C values from the various potential sources of CO_2 makes ^{13}C less useful as a leakage indicator. A large number of measurement locations will be required and statistical approaches will have to be used to interpolate relatively sparse measurements over the area of interest. In addition to measurements of gas composition and variation with depth, seepage flux should be measured using either AC or EC approaches. Areas of anomalous emissions would be obvious places to focus additional sampling and monitoring efforts. Measurements of gas components other than CO_2 associated with the CO_2 sequestration target, e.g., CH_4 if the sequestration target formation is a hydrocarbon reservoir, may also be a promising indicator of potential leakage [12].

Integrated with both the baseline (i.e., pre-injection) characterization measurements and the ongoing monitoring should be numerical simulation [1,2,3] and ecological modeling [e.g., 11]. These analysis efforts should both make use of the measured observations (e.g., as calibration data) as well as make predictions that can be compared against the measurements, with disparities becoming the focus of particular scrutiny as potential leakage or seepage signals. In Figure 4, we present a proposed schedule of integrated monitoring and modeling activities for verification. We emphasize the need for pre-injection activities along with long-term monitoring during and after injection.

Conclusions

Verification of geologic carbon sequestration by monitoring and modeling in the near-surface environment is a challenging but necessary task to ensure the safety and effectiveness of geologic carbon sequestration. The challenge arises because of the large natural background variability in CO_2 concentration and flux. We propose an approach that integrates several different measurements with modeling and analysis. Discrepancies between measurements and model results should be analyzed closely as they may point to evidence of CO_2 leakage or seepage.

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Table 1. Chemical and isotopic signatures related to CO_2 derived from different sources.

CO_2 source	$\delta^{13}C_{CO2}$ ‰	$\Delta^{14}C_{CO2}$ ‰	Near-surface CO_2 conc.	CO_2 conc. depth profile	O_2 conc. depth profile
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.

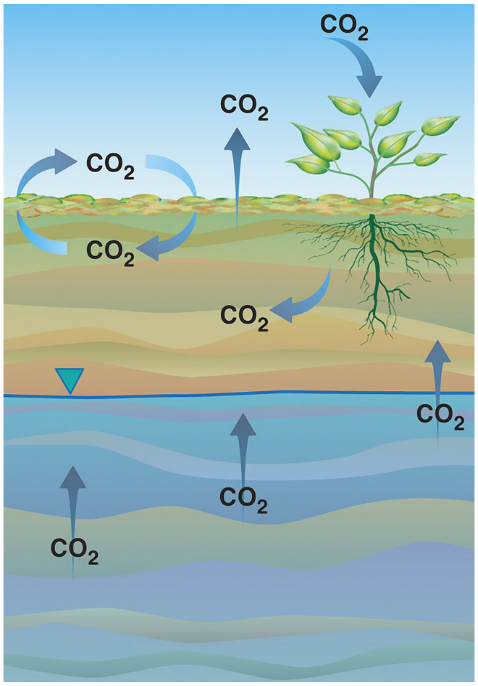

Figure 1. Soil CO_2 sources and sinks, showing from left-right, top-bottom, exchange with the atmosphere, production from decay of organic matter such as leaf litter, uptake by plants, production by root respiration, deep degassing, release from groundwater due to depressurization, and production by oxidation of organic carbon in groundwater at the water table.

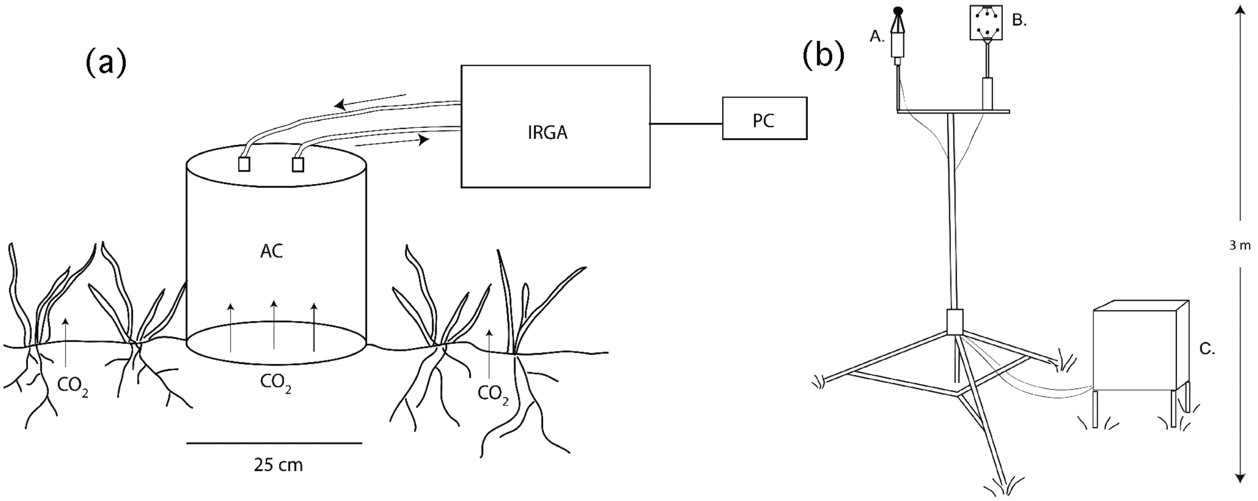

Figure 2. Sketch of (a) accumulation chamber (AC) measurement system of soil CO_2 flux in which contained air is circulated through the AC and the IRGA and the rate of change of CO_2 concentration in the AC is measured by the IRGA and recorded by the PC, and (b) eddy correlation (EC) instrumentation tower showing (A) open-path IRGA, (B) high frequency response sonic anemometer, and (C) box containing power source and datalogger/PC.

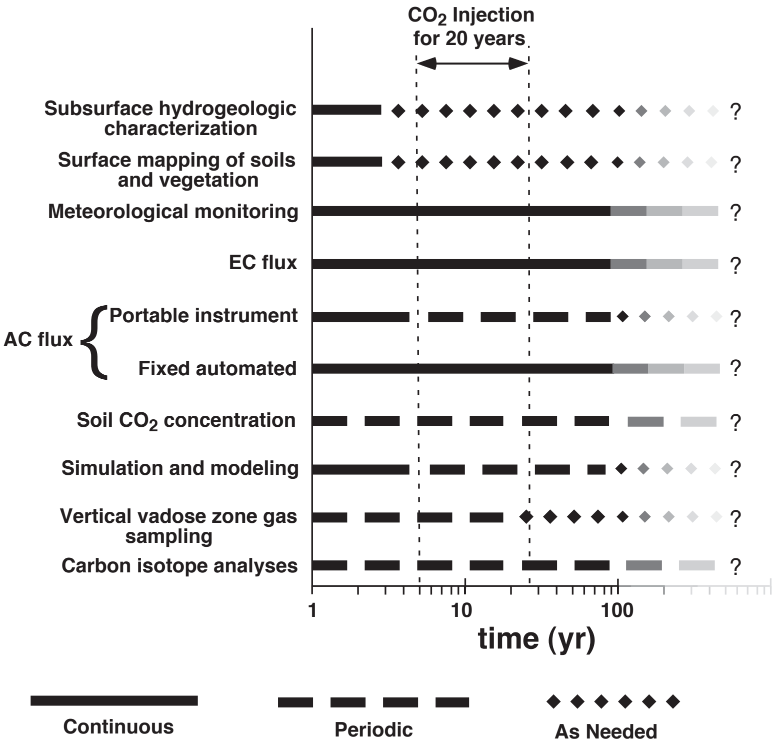

Figure 3. Example activity and schedule chart for CO_2 leakage or seepage signal detection and monitoring showing generalized frequency of measurements (i.e., continuous, periodic, as needed) over time preceding, during, and following CO_2 injection. Lighter shading indicates increasing uncertainty in need for activities at long times following injection.