ELSEVIER
Available online at www.sciencedirect.com
ScienceDirect
Energy Procedia 4 (2011) 3330–3337
Energy Procedia
www.elsevier.com/locate/procedia

GHGT-10

Applying monitoring, verification, and accounting techniques to a real-world, enhanced oil recovery operational CO_2 leak

Bracken T. Wimmer*, Ivan G. Krapac, Randy Locke, Abbas Iranmanesh

University of Illinois, Institute of Natural Resource Sustainability,
Illinois State Geological Survey, 615 E. Peabody Dr., Champaign, IL 61801, USA

Abstract

The use of carbon dioxide (CO_2) for enhanced oil recovery (EOR) is being tested for oil fields in the Illinois Basin, USA. While this technology has shown promise for improving oil production, it has raised some issues about the safety of CO_2 injection and storage. The Midwest Geological Sequestration Consortium (MGSC) organized a Monitoring, Verification, and Accounting (MVA) team to develop and deploy monitoring programs at three EOR sites in Illinois, Indiana, and Kentucky, USA. MVA goals include establishing baseline conditions to evaluate potential impacts from CO_2 injection, demonstrating that project activities are protective of human health and the environment, and providing an accurate accounting of stored CO_2. This paper focuses on the use of MVA techniques in monitoring a small CO_2 leak from a supply line at an EOR facility under real-world conditions.

The ability of shallow monitoring techniques to detect and quantify a CO_2 leak under real-world conditions has been largely unproven. In July of 2009, a leak in the pipe supplying pressurized CO_2 to an injection well was observed at an MGSC EOR site located in west-central Kentucky. Carbon dioxide was escaping from the supply pipe located approximately 1 m underground. The leak was discovered visually by site personnel and injection was halted immediately. At its largest extent, the hole created by the leak was approximately 1.9 m long by 1.7 m wide and 0.7 m deep in the land surface. This circumstance provided an excellent opportunity to evaluate the performance of several monitoring techniques including soil CO_2 flux measurements, portable infrared gas analysis, thermal infrared imagery, and aerial hyperspectral imagery.

Valuable experience was gained during this effort. Lessons learned included determining 1) hyperspectral imagery was not effective in detecting this relatively small, short-term CO_2 leak, 2) even though injection was halted, the leak remained dynamic and presented a safety risk concern during monitoring activities and, 3) the atmospheric and soil monitoring techniques used were relatively cost-effective, easily and rapidly deployable, and required minimal manpower to set up and maintain for short-term assessments. However, characterization of CO_2 distribution near the land surface resulting from a dynamic leak with widely variable concentrations and fluxes was challenging.

* Corresponding author: Tel.: +1-217-244-0163; Fax: +1-217-333-2830.
E-mail address: wimmer@isgs.illinois.edu.

doi:10.1016/j.egypro.2011.02.254

Keywords: Monitoring, verification and accounting; CO_2 leak, Midwest Geological Sequestration Consortium, enhanced oil recovery

1. Introduction

Enhanced oil recovery (EOR) is being tested as a method of increasing hydrocarbon extraction in the Illinois Basin, USA. Substantial additional recovery of valuable liquid hydrocarbons can be attained, in addition to long-term storage of a greenhouse gas by injecting CO_2 into depleted oil fields [1]. As this technology grows and becomes more widely used, attention must be paid to the safety of CO_2 injection and storage. The impact of a CO_2 leak would depend on several factors including location, total volume, and duration. Leaks occurring within the CO_2 delivery infrastructure near the surface likely would have the greatest potential impacts to groundwater drinking sources and surface vegetation. Large leaks should be detectable based on pressure and production responses of the injection formation, as injection formation pressure may decrease. However, slow or diffuse leakage would be much harder to detect and quantify [2]. The Midwest Geologic Sequestration Consortium (MGSC) developed a Monitoring, Verification, and Accounting (MVA) program at multiple field sites to better understand CO_2 injection from multiple perspectives. This includes what can and cannot be detected, which techniques best suit monitoring CO_2 in the subsurface, and understanding the potential changes that have occurred from the original environmental baseline. The MVA team uses surface and shallow sub-surface monitoring equipment at three EOR sites to establish environmental baseline data for each site which allows for monitoring of potential CO_2 leaks into the biosphere.

Figure 1. This map highlights the Illinois Basin, spanning over parts of Illinois, Indiana, and Kentucky. The Sugar Creek EOR site is shown just southwest of Madisonville, KY.

The Sugar Creek EOR site is located just southwest of Madisonville, Kentucky, USA (Fig. 1). CO_2 injection began in May, 2009 at a rate of 20 tons/day, with a sustained surface pressure of 89.6 bar. In July, 2009, personnel at the Sugar Creek site reported a leak from the fibreglass pipeline buried about 1 m underground that was supplying CO_2 to the injection well. The leak was detected when site personnel observed dust being propelled into the air and layers of water vapour hovering near the ground surface in the vicinity of the leak. CO_2 injection ceased upon discovery of the leak, and it was determined that a faulty connection in the supply pipe was the leak source. The MVA team saw this as a unique opportunity to test the performance of monitoring equipment in a real-world situation.

Figure 2. MVA personnel used multiple monitoring techniques to, characterize atmospheric CO_2 concentrations, soil CO_2 fluxes, and thermal signatures at the Sugar Creek EOR leak. Disturbance of the land surface was caused by the leak.

2. Methods

In order to provide a spatially accurate characterization of a three-dimensional CO_2 release, a grid system was established around the leak. The leak occurred in bare soil amongst some dry grass and growing vegetation. The nearest vegetation was located approximately 3 m to the east, southeast, and northeast in the form of shrubs and bushes. The surface expression created by the leak was a hole approximately 1.9 m long by 1.7 m wide and 0.7 m deep. This hole was the center of a grid system for 26 polyvinylchloride (PVC) rings used to measure soil fluxes. These rings were oriented around the leak radially (Figure 3). Rings were named according to their corresponding direction, i.e. NE-1 and NE-2 for the two northeastern rings closest to the leak. Rings were 20 cm in diameter and generally located at distances of 1, 1.5, 3.5 and 5.5 m away from the leak. That grid spacing was used for rings extending in eight radial directions with the exceptions that the 3.5 and 5.5 m distances were not monitored to the southeast or northeast, and the 5.5 m distance was not monitored to the east.

A goal of this investigation was to determine the extent and amount of CO_2 escaping the soil surface via air-filled pores and cracks in the soil [3]. A LI-COR 8100® single-chamber survey system measured the flux of CO_2 from the soil surface. Because only one accumulation chamber was available, fluxes had to be taken sequentially. One flux measurement took approximately three minutes to complete. The monitoring grid was measured twice on

7/6/09 to establish initial conditions. CO_2 injection was then resumed on 7/7/09. Thereafter, additional sets of soil CO_2 flux data were collected from the grid on the morning and afternoon of 7/7/09 and the morning of 7/8/09.

A non-dispersive infra-red gas analyzer (NDIR) measured atmospheric CO_2 and methane (CH_4) concentrations [4]. In order to monitor CO_2 conditions consistently in three-dimensional space, fixed lengths of tubing were secured to a PVC pipe to sample the CO_2 concentrations at heights of 2.5, 25, 50, 75, and 165 cm above ground surface. The same grid pattern used for soil flux measurements was used for NDIR measurements. Measurements were taken sequentially from each tubing port at each grid point. Two sets of NDIR data were collected before CO_2 injection resumed, one on 7/6/09, and one on the morning of 7/7/09. After CO_2 injection resumed, three sets of data were collected from each grid point on 7/7/09, and two sets were collected on the morning of 7/8/09. The experiment was concluded on afternoon of 7/8/09.

Because the rapid release of CO_2 from the ground surface caused extensive freezing of the soil and subsurface water immediately above the leak, thermal imagery was captured using an IR Snapshot model 525™ by Infrared Solutions, Inc. Two aluminum pans were placed about 1.5 m apart from each other on the south side of the leak opening. A third aluminum pan was painted black and placed about 30 cm north of the leak opening. The pans were used as thermal reference points for the thermal images. The unpainted pans displayed a colder thermal signature resulting from their reflectivity, and the painted black pan showed a warmer thermal signature resulting from heat absorption of solar radiation. Thermal images were taken at various times and locations surrounding the leak. Soil temperature was measured by an Omega 865 thermometer to compliment the thermal images. A soil-temperature probe was placed approximately 10 cm into the soil in order to obtain an accurate temperature.

Hyperspectral aerial imagery was collected over the leak area nine times on July 8, 2009 from altitudes of 0.6, 1.1, and 2.1 km. The sensor used on the aircraft did not have wavelengths in the shortwave infrared spectrum to directly detect CO_2. This method utilizes vegetation stress as a proxy for leak detection, and relies on the adverse responses of vegetation to elevated CO_2 concentrations. Slight increases in CO_2 levels can yield positive responses in the vegetation, but at greater CO_2 concentrations, plants can exhibit growth stresses that can be detectable by aerial hyperspectral imagery. Excessive buildup of CO_2 in soil impacts surface vegetation by damaging the ability of roots to absorb oxygen. This inhibits the plants' natural respiration process [5]. GPS coordinates of the leak were used to facilitate the collection of aerial imagery.

3. Results and Discussion

Atmospheric concentrations and soil CO_2 fluxes detected in and above the leak opening were much greater than anticipated on 7/6/09 after injection was terminated. It was later determined that backpressure from the formation was causing CO_2 to flow to the leak because of a malfunctioning check valve at the injection well. Atmospheric CO_2 measurements indicated for the initial condition that CO_2 concentrations were less than 20% CO_2 at 2.5 cm above the ground surface except directly above the leak (Fig. 3). For subsequent readings, elevated CO_2 concentrations were not detected at heights greater than 2.5 cm above the ground surface. Our findings were consistent with Wielopolski and Mitra [5], who concluded that CO_2 buildup occurs mostly near the soil surface-atmosphere interface up to 2.5 cm above the ground and spatial distribution of CO_2 varies greatly depending on weather conditions influencing vertical and lateral mixing.

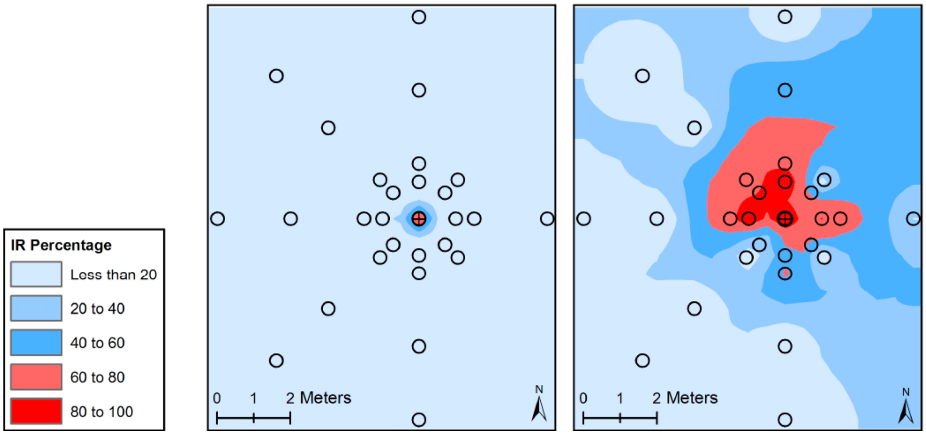

Figure 3. Monitoring grid and representative atmospheric CO_2 concentrations at 2.5 cm above ground level during initial conditions on 7/6/09 (left; with no injection) and on 7/7/09 (right; after injection resumed).

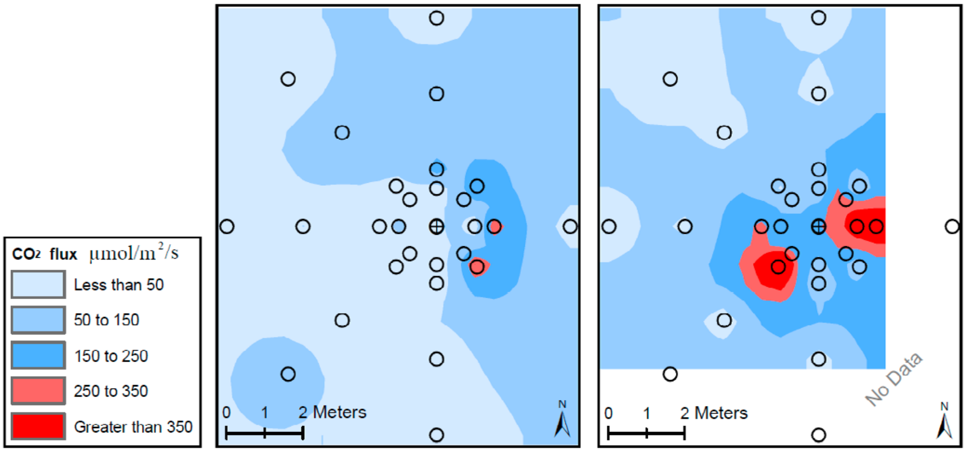

Figure 4. Monitoring grid and representative soil CO_2 fluxes during initial condition on the morning of 7/7/09 (left; with no injection) and on the afternoon of 7/7/09 (right; after injection resumed).

After CO_2 injection was terminated, initial conditions indicated small soil CO_2 fluxes and atmospheric CO_2 concentrations on all grid points except at the leak. Atmospheric CO_2 concentrations measured on July 6 were less than 0.1% at each grid point. At the hole, where the leak was visible, CO_2 concentrations ranged from 86.6% at 2.5 cm above the leak to 0.2% at 75 cm above the leak. Due to the constant (and sometimes violent) activity created by CO_2 pressure buildup in the subsurface, flux data were not collected directly on top of the leak. The grid point in the middle of each image, shown as a target (in Figures 3 and 4), represents the actual leak. Contour intervals represent averaged concentrations or soil CO_2 flux values. As expected, CO_2 fluxes and concentrations were greatest on top of and directly around the leak. For example, at NW4 (5.5 m northwest of the leak), CO_2 concentrations were less than 0.1% and the flux values ranged from 1.97 to 9.05 µmol/m^2/s. In contrast, at SE1 (1 m southeast of the leak), 77.6% CO_2 was measured at 2.5 cm above ground surface on the morning of 7/6/09. Fluxes at SE1 ranged from 10.89 to

267.98 µmol/m^2/s during the experiment. The LI-8100 system has an operational range of 0-3000 ppm CO_2. If CO_2 concentrations during the entire measurement period were more than 3,000 ppm, then the flux value could only be qualified as 'high.' However, if the CO_2 concentration started within the operational range and then exceeded it during the measurement period, data collected within the operational range could still be used to make a quantitative flux estimate.

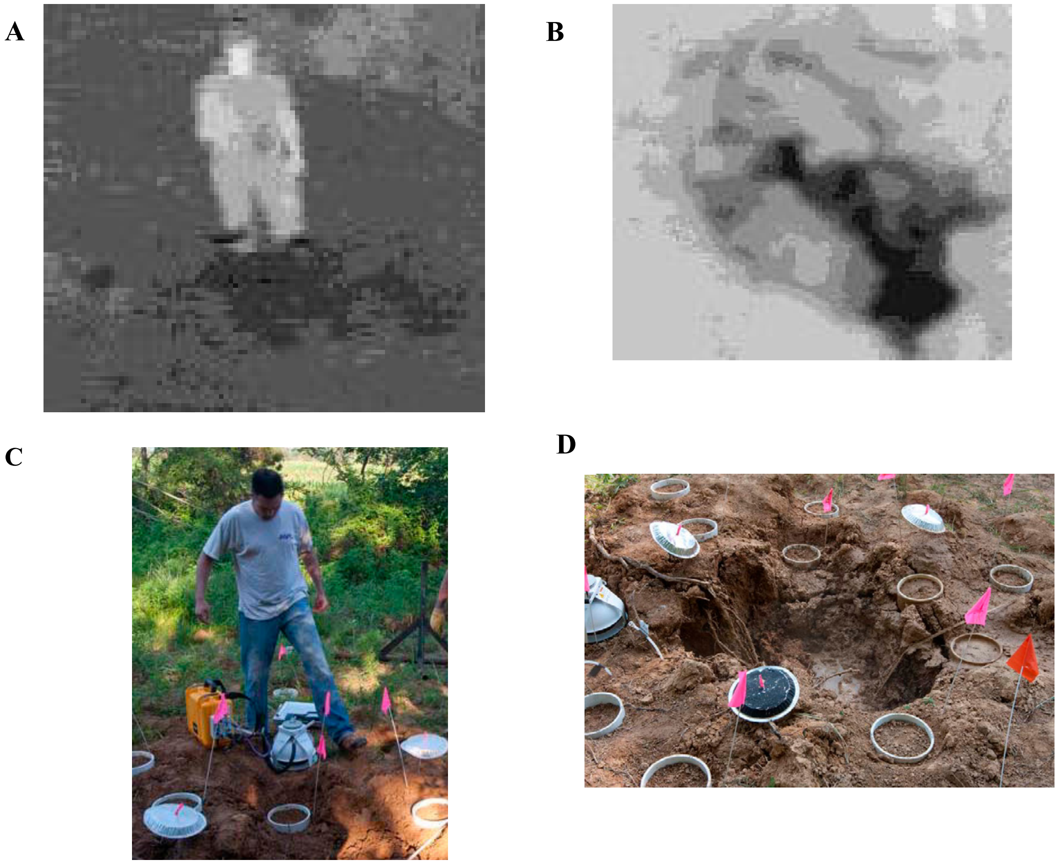

Figure 5. Thermal image A shows the contrast between the warm body (light gray) standing above the cold soil (dark gray) of the leak. Thermal image B was taken looking directly into the hole, with the black representing the coldest thermal signatures in the soil. Photographs C and D depict areas similar to the thermal images for visual orientation.

Thermal imagery detected the contrast in temperature between the warmer soil not affected by the leak from the colder water and soil inside the leak (Figure 5). In the thermal imagery, cold temperatures are shown as darker colors and warmer temperatures are shown as lighter colors. Soil temperature readings showed the coldest temperatures inside and directly adjacent to the hole. On 7/6/09, while air temperature was 27.6º C (81.6º F), the soil in the bottom of the hole was -0.28º C (31.5º F) and soil at the top of the hole was 16.6º C (61.9º F). Table 1 lists soil temperatures collected on 7/7/09 and 7/8/09 to indicate the extent of the thermal influence of the leak on soil temperatures. Even though the soil temperatures were collected on two different days, the data show similar temperature gradients were present. Ambient air temperatures ranged from 26.2º C (79.3º F) to 31.5º C (88.7º F) when soil temperature measurements were being taken. N4, S4, and W4 were the farthest rings from the leak (5.5 m) that showed lower than ambient temperatures.

Table 1. Soil temperatures (in ºC) from the morning of 7/7/2009 (N, NE, S, SW, and W) and on 7/8/2009 (E, SE, and NW) NM means not measured.

Ring # (distance from leak)	N	NE	E	SE	S	SW	W	NW
1 (1.0 m)	14.2	NM	15.2	13.8	13.3	16.6	10.8	13.3
2 (1.5 m)	16.9	NM	18.9	17.3	15.9	18.6	16.9	17.8
3 (3.5 m)	21.0	--	20.7	--	20.5	22.3	21.4	22.8
4 (5.5 m)	21.3	--	--	--	21.1	26.5	21.7	23.8

The hyperspectral imagery was acquired on 7/8/2009, about a week after the leak was first discovered, and no plant stress was observed in the images obtained. Without a sensor to directly detect CO_2, the imagery was reliant on changes in plant physiology related to CO_2-induced stress. This particular technique was not well suited for a leak of such short duration and limited surface influence.

4. Conclusions

The purpose of this investigation was to evaluate the effectiveness of potential shallow monitoring techniques to detect a real-world CO_2 leak. As part of this evaluation, multiple methods were used to characterize the leak. Hyperspectral imagery was not well suited or cost effective for this relatively small, short-term leak. Rapid deployment and maintenance of surface and shallow subsurface monitoring equipment was possible with minimal manpower, however, the active nature of the leak proved to be destructive of the soil surface and interfered with data collection. Thermal imagery was successful in showing a sharp contrast between unaffected soil and frozen soil. Measured soil temperatures were consistent with the thermal images. Soil CO_2 flux data were successful in showing high rates of release of CO_2 into the atmosphere from the leak, however, concentrations encountered outside of the equipment's operational range occasionally caused difficulty in quantifying flux values. Also, leak characterization proved to be challenging with only a single field instrument. For atmospheric measurements, data collection was conducted rather easily and quickly, which proved to be one of the better methods for leak characterization. However, because only one instrument was being used, only one reading could be measured at a time. Elevated CO_2 concentrations were not detected at heights greater than 2.5 cm above the ground surface except directly above the leak. These shallow monitoring techniques provided relatively inexpensive, rapidly deployable, short-term means for leak detection and characterization. However, because of the limitations of the equipment and the very dynamic nature of the leak, trying to detect and quantify unknown CO_2 leaks with these monitoring methods was challenging even at this small scale and could be more difficult at larger scales.

5. Acknowledgements

The Midwest Geological Sequestration Consortium is funded by the U.S. Department of Energy through the National Energy Technology Laboratory (NETL) via the Regional Carbon Sequestration Partnership Program (contract number DE-FC26-05NT42588) and by a cost share agreement with the Illinois Department of Commerce and Economic Opportunity, Office of Coal Development through the Illinois Clean Coal Institute. This manuscript was made possible with the assistance of Chris Korose, Chris Stohr, and Daniel Byers of the Illinois State Geological Survey, and Ken Copenhaver of the University of Illinois at Chicago, Earth Resources Center (funded by the Illinois Clean Coal Institute). A special thanks to all who contributed and to the endless efforts of the MVA team!

6. References

1. Klusman, R.W., Rate measurements and detection of gas microseepage to the atmosphere from an enhanced oil recover/sequestration project, Rangely, Colorado, USA. Elsevier Ltd. 2003; 1825-38.
2. Oldenburg, C.M., J.L. Lewicki, Leakage and seepage in the near-surface environment: an integrated approach to monitoring and detection, 7th International Conference on Greenhouse Gas Control Technologies, 2004.
3. LI-COR® Biosciences, Automated Soil CO_2 Flux System & LI-8150 Multiplexor, Instruction Manual. Lincoln, Nebraska: LI-COR, Inc.; 2007.
4. Geotechnical Instruments® (UK) Ltd., GA2000/GA2000Plus Gas Analyzer Operating Manual. Warwickshire, England: Sovereign House; 2006.
5. Wielopolski, L., S. Mitra, Near-surface soil carbon detection for monitoring CO_2 seepage from a geological reservoir. Springer-Verlag 2009; 307-312.
6. Lewicki. J.L., C.M. Oldenburg, L. Dobeck, L. Spangler, Surface CO_2 leakage during two shallow subsurface CO_2 releases. Geophysical Research Letters, Vol. 34. 2007
7. Lewicki, J.L., G.E. Hilley, C.M. Oldenburg, An improved strategy to detect CO_2 leakage for verification of geologic carbon sequestration. Geophysical Research Letters, Vol. 32. 2005.