Project Title: MONITORING OF GREENHOUSE GAS EMISSIONS FROM SUBSURFACE SOURCES USING REMOTE SENSING

ICCI Project Number: 08-1/US-7
Principal Investigator: Kenneth Copenhaver, University of Illinois Energy Resources Center (ERC)
Other Investigators: Shilpa Venkataraman, Dr. Steffen Mueller, Robert Ealy, ERC
Project Manager: Debalina Dasgupta, ICCI

ABSTRACT

It is estimated that, globally, 28 gigatons of carbon dioxide (CO$_2$) is emitted into the atmosphere from the burning of fossil fuels each year. This number is expected to increase with the increasing demand for energy, a growing global population and emerging national economies. It is imperative to stabilize the CO$_2$ introduced into the atmosphere by anthropogenic activities. This can partially be achieved by geological sequestration which is storing CO$_2$ captured from emissions into rock formations that can retain large quantities of CO$_2$ for long periods of time. The Illinois Basin is a geological formation of choice for carbon sequestration projects since it has three different types of subsurface formations, namely deep unminable coal beds, depleted oil formations, and deep saline reservoirs. The likelihood of a leak from deep geological sequestration is very low, but effective sequestration requires the ability to verify the reliability of the reservoir and ensure that if leaks were to occur they could be discovered in a timely manner and remediated. The safety and effectiveness of geological sequestration efforts is currently being assured through a multitude of measuring and monitoring techniques. This research project carried out by the University of Illinois at Chicago Energy Resources Center (ERC) studies the use of remote sensing tools to monitor for the potential to discover CO$_2$ leakage from geological sequestration sites.

More specifically, this research project investigates the effectiveness of using hyperspectral imagery for detection of leaks from geologically sequestered subsurface CO$_2$ using vegetation changes as an indicator. The sensor used for image collection can detect subtle changes in plant reflectance. Wavelengths best indicative of change in plant vigor were identified. Imagery over the agricultural growing season was collected at the Soybean Free Air Concentration Enrichment (SoyFACE) project plots near the University of Illinois at Urbana Champaign (UIUC), and over a site in western Kentucky where the Midwest Geological Sequestration Consortium (MGSC) is actively sequestering CO$_2$ for research purposes. Trained scouts visited this site to collect ground truth data of CO$_2$ injection wells in the area and a pipe leak that occurred near one injection well. Ground truth information was also collected at the SoyFACE plots. The hyperspectral imagery collected and analyzed in this project establishes that increased CO$_2$ can be detected via remote sensing of vegetation.
EXECUTIVE SUMMARY

Present concerns about climate change include possible links to increasing anthropogenic greenhouse gas emissions. These gases include CO$_2$ which is responsible for 82.3% of these emissions (ICBE, 2000). Geological sequestration is the process of storing isolated CO$_2$ from the earth’s atmosphere in underground pores of rock formations (MGSC, 2010). Efforts are underway to assess CO$_2$ geological sequestration methods, as a form of carbon management to offset emissions from fossil fuel combustion and other human activities. Some technologies needed to monitor certain aspects of CO$_2$ sequestration are commercially available. However, large scale deployment of monitoring devices requires developing much more robust and accurate technologies. The Measuring, Verification, and Accounting (MVA) best practices manual by the National Energy Technology Laboratory (Brown et. al, 2009) identifies various monitoring methods available, but a reliable and cost effective method alone is practical. Site specific MVA systems ensure that injected CO$_2$ remains in the target geological formation.

While geological CO$_2$ injection is an established technology routinely used by oil and gas industries, monitoring for CO$_2$ leaks cannot be described as the same. There are numerous methods of monitoring CO$_2$ leaks, but all have their shortcomings. Deploying CO$_2$ detectors on the ground is a popular method of monitoring leaks. However, these detectors cannot detect early leaks but only ones above ambient CO$_2$ emission limit. Soil and vadose zone gas and ground water chemistry monitoring are popular methods but due to logistic reasons such as timely collection of samples, early detection of a leak may not take place. While these methods of above injection zone release of CO$_2$ monitors certainly provide a sound way to assure safety of CO$_2$ sequestration, the wide spread adoption of geological sequestration efforts by coal fired generating stations in Illinois and elsewhere may provide an opportunity for a different way to monitor the safety and effectiveness of sequestration processes.

Many carbon monitoring methods require trained personnel to visit every pumping station or well in the sequestration site to carry out measurements. In this project, aerial hyperspectral remote sensing is used to indirectly monitor for above ground release of CO$_2$ (in the SoyFACE research plots, soybean crops are exposed to enhanced levels of CO$_2$ & CO$_2$ sequestration site in Sugarcreek, KY). Due to the nature of collecting imagery, wide area data collection is achieved in short period of time. Analysis of the imagery can help in directing personnel to areas where elevated atmospheric CO$_2$ is suspected. Hence, this project is of particular importance to ICCI because monitoring CO$_2$ is an integral part of geological sequestration of CO$_2$.

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Remote sensing is an important tool available for environmental management and monitoring (CSIRO, 2008). It provides up to date, detailed information about land use, land cover and the conditions in an area. In most cases, remote sensing uses a sensor system either on a satellite or airplane to produce images of a location on the earth’s surface. Remotely sensed data is combined with information from other data sources and on-the-ground-observations, called ground truth to get a complete picture of the scene. Remote sensing provides a cost-effective method for mapping and monitoring broad areas. A hyperspectral sensor acquires data at high spectral resolution and the acquired image’s uniqueness lies in its ability to detect subtle features which are not necessarily visible to the human eye. Every pixel in a hyperspectral image has a spectral signature associated with it which is a plot of a specific combination of reflected and absorbed electromagnetic (EM) radiation as a function of wavelength. Hyperspectral remote sensing provides high-resolution spectral data and the potential for remote discrimination between subtle differences in crop signatures.

In this project, the use of remote sensing for surface monitoring of sequestered CO₂ release was investigated. Remote sensing methods can indicate areas where leaks are more likely to occur, therefore, these locations demand higher attention in a sequestration site. This information can assure efficient deployment of CO₂ monitors. Therefore, remote sensing technology will not displace popular and established CO₂ monitors, but will complement monitoring efforts. Imagery for this project was collected using ERC’s hyperspectral sensor. Using this sensor, it is possible to collect imagery at various spatial resolutions. The hyperspectral imagery collected for this project over the two research areas are captured at a high spatial resolution of 0.35m. Similarly, the sensor can collect imagery at a high spectral resolution. For this project, imagery collected was at a spectral resolution of 10nm in the spectral range 400nm-1000nm. It is also possible to simulate other sensor’s imagery or dataset using the project’s hyperspectral dataset.

The ability to detect changes in plant growth and vigor from reflectance measured by remote sensors has been well documented. Research has shown that when exposed to low levels of CO₂, plants respond positively with increased growth and vigor (Hamilton et al. 2008; Wang et al. 2008) while exposure to higher amounts cause the plant to stress and essentially photosynthesize more rapidly than they can transpire, essentially leading to overheating of the plant (Stohr et.al, 2010). Remote sensing can be used as an effective monitoring system that detects subtle changes in plant growth or vigor which can be indicative of a CO₂ leak at a sequestration site. Drawbacks of this indirect method of monitoring include the seasonal and diurnal changes in plant growth and other plant stress factors which may confound the results (Bateson et.al., 2008). The integration of ground information, meteorological data, crop type, soil type etc. in a Geographic Information System (GIS), could provide the foundation of a large-area surveillance system that could identify a plant phenomenon indicative of above-ground release of sequestered CO₂ which can in turn be used for monitoring. The transition between strong absorption in the red and strong reflectance in the near-infrared (red edge), which is characteristic of green vegetation is used to study early plant stress (Munden et.al, 1994, Rurdroff et. al, 1996). Using this property, monitoring sequestration sites using hyperspectral imagery would identify anomalous vegetation spectral signatures indicative
of increased CO2 with the potential for early detection. In combination with a GIS, these areas could be identified and personnel could visit with ground measuring devices to determine if a leak exists. This could give the public and the sequestration group a visual, simple method to ensure compliance and confidence in the sequestration technologies.

This study evaluates airborne hyperspectral imagery in an enhanced CO2 environment to see if imagery can indirectly detect increased CO2 through vegetation response. In this project, plots of soybean crop, exposed to a constant flow of elevated CO2 as part of the SoyFACE project, was monitored over the entire 2009 growing season beginning June 24, 2009. The growth of the crop in the SoyFACE plots was monitored from pre-emergence until senescence (full maturity of pods on plant). An influx of CO2 could induce increased growth or vigor in the crop which can be seen in the near infrared reflectance of the plant using the airborne hyperspectral sensor. Analysis was done to determine if a similar outcome is seen from the vegetation near the well where there was an above ground release of CO2 in the geological sequestration site in Sugarcreek, Kentucky. The vegetation exposed to the leak is evaluated for change in reflectance in the visible and near-infrared regions of the spectral signatures. Mean spectra of the soybean crop under enhanced and ambient CO2 conditions were compared. Statistical analysis was done using the ANOVA model. Also, the best bands for spectral separation were picked out using statistical and separability metrics.

The ERC was the lead investigative body for this effort and coordinated the major aspects of the research. Precision Aviation was responsible for the correct collection of the hyperspectral imagery over both the study sites. The ERC worked with the SoyFACE and ISGS/MSGC cooperators to share data and information, plan image acquisition, and perform field visits.
OBJECTIVES

Objectives of this project were to:

- Capture raw hyperspectral imagery of the SoyFACE plots for ten flights and process (calibrate and georeference).
- Identify enhanced CO₂ release over soybean crops on research plots based on the reflectance of vegetation.
- Capture raw hyperspectral imagery of the MGSC carbon sequestration site in Sugarcreek, KY and process (calibrate and georeference) them for one flight.
- Analyze the SoyFACE plots hyperspectral imagery to observe the effect of enhanced CO₂ exposure on soybean crop. Also, analyze the MGSC site imagery and detect the above ground release of CO₂.

To achieve the objectives, the project work plan consisted of five tasks

- Task 1: Technology review. Characterize current CO₂ monitoring techniques employed or supported by the MGSC and others primarily focusing on accuracy, implementation requirements, and cost.
- Task 2: Collect and pre-process, airborne high resolution hyperspectral imagery over SoyFACE crop plots with enhanced CO₂ levels.
- Task 3: Collect and pre-process, airborne high resolution hyperspectral imagery over MGSC CO₂ sequestration test site in Sugarcreek, KY.
- Task 4: Collect ground data information for locations identified as potential areas for above ground release of CO₂ in both locations.
- Task 5: Data analysis and aggregation.

INTRODUCTION AND BACKGROUND

The work done in this project relates to the ICCI’s program goal priority: Geologic sequestration of carbon dioxide (CO₂).

Increases in greenhouse gas levels, which includes CO₂, in the atmosphere have been the basis of concerns about global warming and climate change. Evidence suggests that a primary reason for the observed rise in atmospheric CO₂ levels is the result of expanded use of fossil fuels, which includes the burning of coal, for energy by humans. Therefore, carbon management and long-term carbon sequestration possibilities could strongly influence future coal projects. Natural carbon sinks are unable to absorb all the CO₂ emitted into the atmosphere when anthropogenic sources are included, therefore efforts are underway to better utilize terrestrial and geological carbon sequestration as a form of carbon management. The Illinois Basin has three different types of subsurface formations, namely deep unminable coal formations, mature oil formations, and deep saline reservoirs (Greenberg, 2005). The research and development program of the ICCI lays emphasis on carbon management in the Illinois Basin. One of their main focus areas is “Geologic sequestration of CO₂” and since monitoring for CO₂ leaks to the subsurface
is an integral part of effective sequestration, this project, which aids in monitoring sequestered CO₂, contributes towards ICCI’s research program.

Many analyses have shown that the Illinois Basin provides opportunities for geological carbon sequestration and efforts are underway to further explore this opportunity (Chen et al., 2005). In fact, Archer Daniels Midland (ADM), MGSC, and the Illinois State Geological Survey (ISGS) are currently working together on a number of carbon sequestration projects. One large project involves the capture and sequestration of CO₂ from ADM’s ethanol plant in Decatur, Illinois (Damiani, 2008). In this effort, CO₂ is stored in the tiny spaces of porous rock of the Mount Simon Sandstone, a major regional saline-water-bearing rock formation in the Illinois Basin. The project started the sequestration process in the fall of 2009. ISGS is working with ADM to demonstrate the safety and effectiveness of the geological sequestration process. Multiple ground-based CO₂ sensors spread throughout the property monitor for the unlikely scenario that sequestered CO₂ would release to the surface. Despite research to indicate the longevity and effectiveness of geological CO₂ sequestration, ADM, MGSC and the U.S. Department of Energy feel it is important to effectively monitor the site to ensure public safety in the unlikely event of an actual above-ground release of sequestered CO₂.

The MGSC is a combined effort by the Illinois, Indiana, and Kentucky State Geological Surveys and covers the entire state of Illinois, southwest Indiana and western Kentucky. It is one of seven regional partnerships selected by the U.S. Department of Energy to investigate and determine the best approaches for capturing and sequestering CO₂. Researchers involved in these efforts share a strong sense of confidence based on research that once sequestered, CO₂ will not reach the surface from the deep underground geological formations (Benson, 2006), but the government and public would still like to see efforts to monitor for any possible above-ground releases. The ERC has a partnership with the ISGS to share information collected on the SoyFACE plots and at the western Kentucky CO₂ sequestration site at Sugarcreek. Ground truth data collected by ISGS personnel using their surveying equipment was used by ERC personnel for analysis of the hyperspectral imagery.

EXPERIMENTAL PROCEDURES

The SoyFACE research facility is located near the University of Illinois Urbana Champaign. It is a research design which has soybeans grown under fully open air conditions and exposed to a variety of atmospheric CO₂ levels without isolating the plants from environmental effects such as rainfall, sunlight, and insects. (Miyazaki et al., 2004). The main purpose of this innovative facility is to study crops under production field conditions in an atmosphere that is anticipated for the middle of this century, namely one with higher levels of CO₂ and ozone. Cutting edge technology is employed to simulate these atmospheric conditions. Figure 1 shows the location of the SoyFACE plots near UIUC in Champaign county, Illinois.
Figure 1. SoyFACE plots located in Champaign County, Illinois

At the center of the research plots are rings (each approximately 70 feet in diameter) of pipes that release CO₂ or ozone into the wind as it flows across the crop. A computer continuously measures wind speed, wind direction, and the gas concentration within the ring. The CO₂ is released into the naturally moving air so that the concentration within the ring is elevated to a preset level. The SoyFACE experiment site and the layout with corresponding treatments of the research plots are shown in Figure 2. In the elevated CO₂ plots, the pipes release approximately 3 tons per plot per 16 hour day, or 0.2 tons/hour of atmospheric CO₂. This release results in CO₂ levels of approximately 560 ppm, the level predicted for the year 2050 if current trends continue. These are compared to soybean grown at ambient CO₂ levels of approximately 380ppm (Miyazaki et al, 2004). There are four plots of each experimental condition. The 4 elevated CO₂ plots and the 4 ambient control plots were used for analysis in this project.

A simple calculation shows that a 300 MW coal fired power plant (operated at 100% capacity factor) emits about 386 tons of CO₂ per hour. If we assume that all of this CO₂ is sequestered, the 0.2 tons CO₂/hour per plot at SoyFACE would simulate about a 0.05% leakage rate from the subsurface storage of such a power plant. These release scenarios are similar to other carbon leakage scenarios modeled in the literature (Benson and Hepple, 2005).
Figure 2. 2009 SoyFACE Aerial Photograph and Layout of Plot Site

Twelve inch by twelve inch white square panels were laid around each plot in a grid pattern and GPS points of the panels were collected (Figure 3) as well as other static features (buildings, road intersection, etc) to aid image geo-referencing. The Global Positioning System (GPS) points of the panels are also used to identify the boundaries of a plot in the imagery.

Figure 3. Grid pattern of the 12 inch square panels over which GPS points are recorded

Hyperspectral imagery of the SoyFACE plots was captured during the 2009 soybean growing season from late June to early October. The imagery collection time was typically +/- one hour of solar noon under clear weather. Sometimes, due to logistical reasons, imagery was collected under partly sunny conditions. The SoyFACE imagery
was captured at an altitude of 2000 feet above ground level at an aircraft speed of 100 knots creating 0.35m spatial resolution pixels from the second flight onward as it was determined that the 0.5 meter resolution imagery captured at 3500 feet had very few pure pixels for analysis. Table 1 lists the ten flights that captured hyperspectral imagery over the SoyFACE plots and the weather and soybean conditions.

Table 1. 2009 SoyFACE flight schedule

<table>
<thead>
<tr>
<th>Date</th>
<th>Altitude (ft.)</th>
<th>Resolution (m)</th>
<th>Time</th>
<th>Conditions</th>
<th>Field Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>6/24/2009</td>
<td>3500</td>
<td>0.5</td>
<td>10:12am</td>
<td>Sunny</td>
<td>Pre-emergence</td>
</tr>
<tr>
<td>7/17/2009</td>
<td>3500, 2000</td>
<td>0.5, 0.35</td>
<td>10:47am</td>
<td>Partly Sunny</td>
<td>20% Emergence</td>
</tr>
<tr>
<td>7/21/2009</td>
<td>2000</td>
<td>0.35</td>
<td>11:14am</td>
<td>Partly Cloudy</td>
<td>30% Emergence</td>
</tr>
<tr>
<td>7/27/2009</td>
<td>2000</td>
<td>0.35</td>
<td>10:32am</td>
<td>Partly Cloudy</td>
<td>60% Emergence</td>
</tr>
<tr>
<td>8/2/2009</td>
<td>2000</td>
<td>0.35</td>
<td>12:17pm</td>
<td>Sunny</td>
<td>80% Canopy</td>
</tr>
<tr>
<td>8/12/2009</td>
<td>2000</td>
<td>0.35</td>
<td>9am, Noon,3pm</td>
<td>Sunny</td>
<td>Full Canopy</td>
</tr>
<tr>
<td>8/25/2009</td>
<td>2000</td>
<td>0.35</td>
<td>10:32am</td>
<td>Partly Cloudy</td>
<td>Full Canopy</td>
</tr>
<tr>
<td>8/31/2009</td>
<td>2000</td>
<td>0.35</td>
<td>11.06 am</td>
<td>Sunny</td>
<td>Full Canopy</td>
</tr>
<tr>
<td>9/3/2009</td>
<td>2000</td>
<td>0.35</td>
<td>10:58am</td>
<td>Sunny</td>
<td>Full Canopy</td>
</tr>
<tr>
<td>10/2/2009</td>
<td>2000</td>
<td>0.35</td>
<td>11:18am</td>
<td>Partly Cloudy</td>
<td>Senescence</td>
</tr>
</tbody>
</table>

In late June, The MGSC notified ERC that a CO2 sequestration site in Sugarcreek, KY was experiencing an above ground CO2 release from a below ground source caused by a faulty PVC pipe joint. Pressurized CO2 caused a bulge in the ground before being released above ground. The release was maintained by the contractor for several days in early July in order to allow the MGSC monitoring team to test equipment. MGSC personnel notified ERC and a flight was planned on July 8, 2009. Figure 4 shows the Sugarcreek site in Hopkins county, KY. Hyperspectral imagery was collected over the site at multiple resolutions. The images were collected at various altitudes to establish the minimum mapping unit for CO2 detection. Table 2 shows the flight lines at the Sugarcreek site.
RESULTS AND DISCUSSION

Task 1: Technology review

There are several MVA methods that can be implemented to assure CO$_2$ injection into deep geological formations is protective of human health and the environment. They are broadly categorized into atmospheric, near-surface, and sub-surface monitoring techniques.

Table 3 is a list of some example MVA techniques that have been tested or proposed in geological CO$_2$ storage projects. The benefits and challenges of each method is provided (Brown et. al, 2009).
Table 3. MVA techniques used or proposed in CO₂ storage projects.

<table>
<thead>
<tr>
<th>Monitoring Technique</th>
<th>Type of monitoring</th>
<th>Description</th>
<th>Benefits</th>
<th>Challenges</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂ detectors</td>
<td>Atmospheric</td>
<td>Sensors for monitoring CO₂ in air.</td>
<td>Inexpensive and portable.</td>
<td>Detect leakage above ambient CO₂ emissions.</td>
</tr>
<tr>
<td>Tracers</td>
<td>Near-surface</td>
<td>CO₂ soluble compounds injected along with the CO₂ into the target formation. Reach technique is permanent.</td>
<td>Used to determine the flow direction and early low-mass leak detection.</td>
<td>Many of the CO₂ soluble tracers are green house gases (GHGs), therefore, add to risk.</td>
</tr>
<tr>
<td>Groundwater monitoring or Soil and Vadose Zone Gas monitoring</td>
<td>Near-surface</td>
<td>Sampling of water/gas in vadose zone and near surface soil for basic chemical analysis. Reach technique is permanent.</td>
<td>Early detection prior to large emissions.</td>
<td>Significant effort for null result (no CO₂ leakage). Relatively late detection of early CO₂ emission.</td>
</tr>
<tr>
<td>Synthetic Aperture Radar</td>
<td>Near-surface</td>
<td>A satellite-based technology in which radar waves are sent to the ground to detect surface deformation.</td>
<td>Large-area monitoring. Portable.</td>
<td>Best used in environments with minimal topography, minimal vegetation, and minimal land use. Useful in time lapse.</td>
</tr>
<tr>
<td>Annulus pressure monitoring</td>
<td>Subsurface</td>
<td>A mechanical integrity test that can be done</td>
<td>Reliable test with simple equipment. Technique is portable.</td>
<td>Injection process has to be stopped during testing.</td>
</tr>
</tbody>
</table>
constantly on the annular volume of a well to detect leakage from the casing, packer or tubing.

### Gamma ray logging

**Subsurface**

Use of natural gamma radiation to characterize the rock or sediment in a borehole.

Common and inexpensive measurement of the natural emission of gamma rays by a formation. Technique is portable.

Subject to error when a large proportion of the gamma ray radioactivity originates from the sand-sized detrital fraction of the rock.

### Aqueous Geochemistry

**Subsurface**

Chemical measurement of saline brine in storage reservoir.

Coupled with repeat analyses during and after CO$_2$ injection can provide mass balance and dissolution/mineral trapping information. Technique is portable.

Cannot image CO$_2$ migration and leakage directly. Only near-well fluids are measured.

Atmospheric monitoring is the least expensive of all monitoring methods since open access is available above the ground. Measurements are also instantaneous and a rapid response to large leaks is possible. However, a major challenge is the dilution of CO$_2$ between the measurement meter and the release point since the atmosphere is a mixed medium. In other words, if the release point is many meters from any measurement sensors, the meter will not detect the CO$_2$ as it mixes with the atmosphere. Also, since there are several sources of CO$_2$ emission, such as soil, plants, combustion, etc., a considerable amount of variability is introduced, so only very large leaks can be detected accurately. Furthermore, measurement of a leak on the surface is a retarded response compared to leak detection in the injection zone which would delay response time and risk management. CO$_2$ detectors, Laser systems and LIDAR, Tracers, Advanced leak detection system, and Eddy covariance are some other, less common atmospheric monitoring techniques (Brown et al., 2009).

Near-surface monitoring techniques are available at low costs. Since residence time of CO$_2$ is longer than in the atmosphere, there is an increase probability of detecting CO$_2$ which has escaped the sequestration location below. But as in the case of atmospheric monitoring, several sources of CO$_2$ emission are present and several samples have to be recorded. Groundwater monitoring, thermal imaging, soil, vadose zone gas monitoring
and ecosystem stress monitoring are some other examples of near-surface monitoring techniques (Brown et. al, 2009).

Subsurface monitoring techniques are used to predict the exact location of CO₂ which could be a result of a release from the sequestration location. The volume of the release can also be identified. The challenge of the technique includes high costs to get direct access to the possible leak zone. No techniques are present to measure the CO₂ in situ, therefore indirect or inferential methods need to be used to assure that unacceptable amount of CO₂ is not leaking from the injection zone. Injection well logging, Annular zone pressure monitoring, Sonic logging, Time-lapse gravity, Crosswell seismic survey, Aqueous geochemistry are some subsurface monitoring techniques (Brown et.al, 2009).

In comparison to all the popular methods mentioned in Table 3, remote sensing using aerial hyperspectral imagery as carried out in this project, has several advantages, the primary being easier wide area monitoring in a short time frame. Imagery, unlike many other methods, could capture information for the entire sequestration above-ground site not just point data. Vegetative health, which could be a good indicator of CO₂ leakage, can be estimated easily using aerial hyperspectral imagery using already established methods. A potential disadvantage of remote sensing is that it needs favorable weather conditions to operate the aircraft. Also it is a technology with its application being fairly new to geological sequestration.

The MGSC uses a combination of techniques that include technique atmospheric, near-surface, and subsurface monitoring. Samples of water or gas readings are taken on a regular basis as a part of the MVA process to assure that if a leak occurs; it is detected and reported in a timely manner. The methods that have been put in place are (Iranmanesh et. al, 2009):

1) Atmospheric monitors. This technique is permanent.
2) Monitoring CO₂ gas concentration in vadose zone and annular zone in oil field wells. This technique is portable.
3) Monitoring groundwater quality in monitoring wells and residential wells. This method is portable.
4) Monitoring brine chemistry. This technique is portable.
5) Monitoring with aerial color infrared imagery. This technique is portable.
6) Monitoring using operational components such as pressure, temperature, CO₂ injection rate, and volume. This technique is permanent.
7) Monitoring shallow geophysical surveys. This technique is portable.
8) Monitoring by geochemical and underwater modeling. This technique is permanent since the model is based on data that is continuously collected.

Monitoring methods have been implemented in pilot sites in Loudon Field in St. Elmo, IL, Mumford Hills in Griffin, IN, and Sugarcreek in Earlington, KY. Ground surface release of CO₂ in the Sugarcreek site in July 2009 was successfully detected using pressure and gas sampling.
Most of the monitoring methods mentioned above require trained personnel to visit every pumping station or well in the sequestration site to carry out measurements with portable devices. These measurements are also point-source. The potential exists for leaks to occur within fissures anywhere in the sequestration site. Remote sensing offers a simultaneous view of the entire sequestration site. Wide area data collection is achieved in short period of time. Analysis of the imagery can help in directing personnel to areas where elevated atmospheric CO₂ is suspected. Hence, for efficient deployment of portable monitoring devices in a widespread area, remote sensing can be used as a tool to detect subsurface CO₂ release consequently reducing costs involved in data collection and analysis. Research has indicated the potential to identify CO₂ leaks from sub-surface sources based on the reflectance of vegetation (Stohr, in press). Stohr’s trial was conducted to determine the efficacy of using airborne thermal infrared imagery to identify CO₂ affected plants. The research showed that when exposed to low levels of CO₂, plants respond positively with growth while exposure to higher amounts cause the plant to stress and essentially photosynthesize more rapidly than they can transpire, essentially leading to overheating of the plant. The ability to detect changes in plant growth and vigor using remote sensing techniques to measure reflectance has been well documented as well (Hamilton et.al (2008) and Wang et. al (2008)).

For the research in this study, the SoyFACE plots at UIUC and MGSC sequestration sites were monitored using aerial hyperspectral imagery to identify anomalous vegetation spectral signatures of a plant reflectance indicative of increased CO₂. Imagery of the plots that are exposed to enhanced CO₂ conditions is captured using a hyperspectral sensor. Hyperspectral imagery used in this project exhibits spectral curves from the visible to the near infrared (NIR) region which indicate changes in vegetation. Change in spectral curves over the soybean growth season were analyzed and observed for changes potentially due to increased CO₂ exposure.

**Task 2: Collect and pre-process airborne high resolution hyperspectral imagery over SoyFACE crop plots with enhanced CO₂ levels**

The hyperspectral instrument used by the ERC for the project is a simple, low cost instrument consisting of a digital camera developed by the Cooke Corporation, a prism-grading filter developed by Specim and a lens developed by Schneider Optics. The system is controlled by software developed for ERC on a personal computer. Figure 5 shows the image collection process using ERC’s hyperspectral sensor.
The lens focuses reflected light into the prism-grading filter which only allows the light from specific wavelengths to exit in specific locations. The wavelength-split light is then focused onto the ccd-array of the camera (Mao, 2000). Each line on the ccd-array (1600 lines) of the camera records the reflected light for separate wavelengths. Software then “rotates” the ccd-array image from a 1 band 1600 line image into a multiple (up to 1000) band 1 line image. The movement of the plane then captures the next parcel of land. This is continued until the entire area of interest is collected. The hyperspectral sensor can collect up to 4,000 lines at a 240 band spectral resolution before having to stop temporarily to save data to a computer hard drive. For the SoyFACE plots, the hyperspectral imagery was collected at the following parameters: 0.35 meter spatial resolution and a spectral resolution of 100 bands in the visible and NIR regions from 400 nm to 1,000 nm. Table 4 shows the wavelengths corresponding to regions in the electromagnetic spectrum. Imagery was collected from a Cessna210 fixed wing aircraft at a height of 2000 feet above ground level. The aircraft is outfitted with a Zeiss gyro-stabilized mount to minimize image distortion.

<table>
<thead>
<tr>
<th>Wavelength (nano meters–nm)</th>
<th>Region in the Electromagnetic spectrum</th>
</tr>
</thead>
<tbody>
<tr>
<td>400-500</td>
<td>Visible – Blue</td>
</tr>
<tr>
<td>500-600</td>
<td>Visible – Green</td>
</tr>
<tr>
<td>600-700</td>
<td>Visible – Red</td>
</tr>
<tr>
<td>700-1000</td>
<td>Near Infra Red</td>
</tr>
</tbody>
</table>

The camera system was calibrated to at-sensor radiance and well characterized. The imagery was corrected for atmospheric and camera noise. The inherent camera noise and calibration to at-sensor radiance was performed based on calibration parameters.
developed at the Stennis Space Center Camera Calibration Laboratory. As soon as the flight landed after capturing the imagery, the imagery was calibrated to at-sensor radiance using software developed in-house, and then the at-sensor radiance values were subsequently calibrated to surface reflectance using Navy Research Laboratory’s TAFKAA atmospheric calibration model (B.Gao and M.J. Montes, 2004). Figure 6 shows an example hyperspectral image of the SoyFACE plot before and after calibration. The spectral profile of the calibrated image is typical of vegetation. The green in the visible region has a higher reflectance value compared to the blue and red region of the spectrum. The infrared region has a high value of reflectance which indicates plant vigor.

The imagery was both rectified and geographically referenced. An on-board inertial navigation system with global positioning system provided degrees for the aircraft’s roll, pitch, and yaw 100 times per second and geographic location once per second. The geographic location was interpolated using aircraft velocity to match the aircraft attitude parameters (100 times per second). In-house software that applies the photogrammetric corrections based the airplane’s locational parameters is run on the imagery upon landing of the plane. The calibrated image is overlaid over a reference image to check for approximate alignment. Figure 7 shows the sensor altitude correction and approximate georeferencing.

Figure 6. SoyFACE plot before (left) and after (right) calibration
Following this step, the image is georeferenced using GPS points of the panels that were placed on the boundaries of each research plot in the SoyFACE site. Figure 8 shows georeferencing process. Reflectance values of the georeferenced, calibrated airborne imagery were extracted from known locations of CO₂ levels. This information was saved to ASCII files for statistical analysis. The entire above mentioned image processing steps is shown in a flow diagram in Figure 9.
Task 3: Collect and pre-process airborne high resolution hyperspectral imagery over carbon sequestration site at Sugarcreek, KY

Image preprocessing is the fundamental step for image analysis. Careful preparation of imagery leads to reliable results. The steps followed were similar to those explained in Task 2. Imagery was collected over the carbon sequestration site in Sugarcreek, KY using ERC’s hyperspectral camera. The camera system was placed on a Cessna airplane. and imagery was collected at multiple altitudes and angles (direction) as mentioned in Table xx. This was done so that image of the injection well where the leak occurred could be captured was done at the best possible elevation and direction. After careful examination it was determined that the images captured at altitude of 2000ft. at a spatial resolution of 0.35m was best for analysis due to higher pixel purity. At sensor radiation calibration was performed using ERC’s in-house software. This was followed by applying atmospheric calibration to the image using NRL’s TAFKAA model. This was followed by altitude correction and approximate georeferencing. This was done to compensate for the roll, pitch, and yaw of the airplane during image collection. The image was georeferenced to perfectly align the hyperspectral image over an orthorectified aerial photo. The final processed imagery was used for analysis.

Task 4: Collection of ground data information for locations identified as potential areas for above ground release of CO₂ in the SoyFACE plots and sequestration site in Sugarcreek, KY

At the SoyFACE site, GPS points were collected using survey grade GPS receivers, often used for very specialized activities where high degree of horizontal and vertical positional accuracy is required. Twelve inch square white panels were placed over posts within the project. These GPS points aid in extracting pixels from within the project to analyze for
enhanced CO₂ exposure. Figure 10 shows the panels in the SoyFACE project site. Also, points corresponding to static features near the plots were recorded. These GPS location of the panels help in geo-referencing the image collected over the site.

![White 1x1 foot panel](image)

Figure 10. Geo-referencing panels on SoyFACE project site

UIC and ISGS personnel traveled to the sequestration site in Sugarcreek, KY to collect ground truth information. In the Sugarcreek, KY site, sequestration was achieved by injecting CO₂ underground through specific geological sequestration wells, usually in or near a corn field. These CO₂ injection wells were locations for potential leaks. The points were collected using a Leica survey grade GPS. The accuracy of the surveying system is within 2-3 centimeters. The points collected correspond to the actual leak that occurred due to faulty connection between PVC pipes at the site and other CO₂ wells in the sequestration site. Figure 11 shows the surveying system that was used to collect points. A total of 15 points were collected at the site. Over a period of 15 minutes, 300 static points were collected at 5 second intervals using a GPS receiver. The surveying equipment was tied to a base station which was continuously collecting data points by linking to GPS satellites. All 300 points were averaged to get the exact location of a point. Each of the point locations was documented in detail with respect to the surrounding conditions and location. Also, the distance from the road, height at which GPS receiver was stationed, and time of day were recorded. These points were used to georeference the hyperspectral imagery to real world coordinates so the exact location of the leak in the imagery could be identified and analyzed.
Task 5: Data Analysis and Aggregation

The imagery is ready for analysis following georeferencing. After the pre-processing steps, the resultant image has 86-bands as several bands in the blue and near-infrared are removed from analysis as a result of noise associated with ccd-array sensitivity. Spectral signatures of vegetation from the SoyFACE imagery were extracted for pixel values corresponding to the soybeans in an enhanced CO$_2$ environment and soybeans under control ambient atmospheric CO$_2$ levels. Similarly, the Sugarcreek imagery was pre-processed and the pixel values corresponding to the location of the CO$_2$ leak, and background vegetation were extracted. Analysis of the imagery to determine if enhanced CO$_2$ environment in vegetation could be detected was done using the extracted data.

Mean spectral signatures of the two plots types (enhanced and ambient CO$_2$) in the SoyFACE research area were calculated and plotted for all flight dates (Figure 12). Statistical separability between the signature types could be is an indicator of increased CO$_2$ exposure. The separability between the two spectral curves for each CO$_2$ level was observed in the 7/27/09 and 8/2/09 data. Maximum separability occurs in the 8/2/09 data in the near infrared (NIR) region of the spectrum. The crop that grew under enhanced CO$_2$ exposure grew more vigorously when compared to the crop under ambient conditions. Next, the difference in signatures was calculated. From Figure 13 it is seen that on 8/2/09, the difference is at maximum, indicating that separability is high.
Also, an analysis of variance (ANOVA) was performed on the reflectance bands to determine the significant bands that show separability between the two data sets. The F-values and P-values were plotted and shown in Figure 14 (a), (b). Separability peaks in the NIR region consistently for all growing days around 750nm and in the blue region during senescence. The F-values in the figure indicate that separation between the two CO₂ levels increases as the crop progresses throughout the soybean growing season and then declines as the crop goes into senescence. Similarly, the P-values also indicate the
significance of bands. The lower the value of P, the higher the significance of a band. From Figure 14 (b) it is seen that the significant bands are in the blue (during senescence) and NIR regions (during normal growing days).

Figure 14. Analysis of Variance (a) F values (b) P values

The mean signature analysis confirmed separability between CO2 enhanced soybean plots and soybean plots under ambient/ control conditions existed and indicated this separation occurred because the soybean plots in the enhanced environment exhibited a healthier vegetation signature. The mean signature analysis, however, could not indicate variance in each population (enhanced CO2 and control) which could interfere with the ability to identify vegetation in an enhanced CO2 environment. The ANOVA test confirmed that the variability was not significant enough, at least in the near-infrared, to interfere with separation. Essentially, the mean separation analysis showed where and how separation occurred while the ANOVA confirmed strength of this separation.

Next, an analysis was done to extract the best bands for the SoyFACE dataset for each of the dates imagery was captured. The best band algorithm was based on high-order statistical moment, skewness, which has a high chance of containing important target information (Du, 2003). The metric used for selecting bands is Jeffries Matusita distance which indicates band separability (Venkataraman, 2005). Figures 15 and 16 show the best bands that can identify elevated CO2 and ambient/ control plot signatures effectively. The best bands during the growth season are typically in the NIR region and also in the blue region for CO2 detection. During the peak of growth season, as the soybeans reach full canopy, several bands are selected in the NIR region. However, for the control plots, there is no particular pattern.
Three flight lines (5, 5a, 5b) were captured at 2000ft at 0.35m spatial resolution. The exact location of the leak in the Sugarcreek site was recorded using the survey grade GPS. Figure 17 shows the small leak area. The leak hole was smaller than 0.5m diameter. Moreover, the shadow in the leak area from nearby tree line made it difficult to extract a pure spectral signature of the vegetation that might be exposed to the leak.
Hence, from the spectral signatures extracted from the leak site it was not possible to see the change in reflectance of vegetation associated with increase in CO2 levels or directly detect CO2. Shadow dominated the spectral signature and therefore, any analysis done led to inconclusive results, but, since the CO2 had only been leaking for three days prior to image collection the chance of it impacting vegetative health may not have occurred yet. Shadow effects from neighboring objects such as trees and buildings will need to be taken into account when using imagery for detection of CO2.

CONCLUSIONS AND RECOMMENDATIONS

A study was conducted at two sites for the detection of elevated CO2 levels from hyperspectral imagery using vegetation as a proxy indicator. The first site was a controlled environment at the University of Illinois SoyFACE project plots in Champaign, IL. The plots here are fitted with CO2 and ozone enrichment equipment and the crop is exposed to a predetermined level of gas. The second site was a CO2 sequestration site identified by the MGSC in Sugarcreek, KY. In this site, CO2 is injected into the geological formations through subsurface wells. The key findings relative to detection of CO2 can be summarized as follows:

- Enhanced CO2 exposure can be detected in soybean crops during certain times of the year. During the growing season, the early August imagery showed that the CO2 enriched crop growth was more vigorous.
- CO2 leak in the sequestration site could not be detected and a definitive result could not be reached. This was mainly due to the shadow from nearby trees where vegetation was exposed to the leak and the fact that the vegetation had not been exposed to the CO2 for an extended period of time.
A sensor that is capable of capturing wavelengths for direct detection of CO₂ will be more practical in cases such as Sugarcreek site since indirect detection through vegetation will not be required. Strong CO₂ absorption is seen in the short wave infrared (SWIR) region of the electromagnetic spectrum. Therefore, a sensor ranging from 1000nm to 2500nm would be useful for direct detection of CO₂.

REFERENCES


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