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Review

Remote sensing of CO₂ leakage from geologic sequestration projects

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ABSTRACT

Monitoring for leak hazards is an important consideration in the deployment of carbon dioxide geologic sequestration. Failure to detect and correct leaks may invalidate any potential emissions benefits intended by such projects. Presented is a review of remote sensing methods primed to serve a central role in any monitoring program due to their minimally invasive nature and potential for large area coverage in a limited timeframe or in real-time as a continuous monitoring program. Methods investigated were divided into those capable of indirect detection of carbon dioxide leakage, such as monitoring for vegetative stress and ground surface deformation, and those that directly detect gaseous and atmospheric compounds, by means of such tools as Open-Path Fourier Transform Infrared or Tunable Diode Lasers. Both direct and indirect methods present viable means of detecting a leak event, though ultimately, a robust approach will incorporate multiple monitoring tools that may include both direct and indirect remote sensing methods.

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1. Introduction

Carbon dioxide is a greenhouse gas, recognized for its role in altering the global climate by trapping heat within the Earth's atmosphere. According to the Intergovernmental Panel on Climate Change (IPCC), the industrialization of civilization has increased the production and emission of carbon dioxide (CO₂) into the atmosphere, leading to concern about climate change and the effects this may have on the environment (Pachauri and Reisinger, 2007). Annual global anthropogenic emissions of carbon dioxide were estimated around 38 gigatons (Gt) for 2004, and account for nearly 80% of all greenhouse gas emissions from anthropogenic sources (Benson and Myer, 2002; Pachauri and Reisinger, 2007). The energy sector is a primary contributor of CO₂ emissions, with estimates placing their current levels above 30 Gt (International Energy Agency [IEA], 2013). Estimates for stabilizing the climate at a 2° centigrade increase in global temperatures call for reducing these emissions by one third in the next twenty years, highlighting the need for immediate action (IEA, 2013).

One method of reducing carbon emissions to combat global climate change is through carbon sequestration (Benson and Cook, 2005). Carbon is captured at a source such as a gas production or similar industrial facility, then injected into a safe underground repository such as a brine formation or depleted oil or gas reservoir (Hepple and Benson, 2005). The injected carbon is trapped within the formation due to geological features that might include an impermeable caprock that prevents upward migration of the injected CO₂, or a mineral composition that reacts with the injected CO₂ and precipitates a stable carbonate form (Benson and Cook, 2005; Lackner, 2003). This reduction strategy is particularly applicable to the energy sector, as a large share of emissions from energy production are point sources, rather than diffuse sources, and therefore easier to capture. The idea behind this process is that sequestering carbon underground will prevent carbon dioxide from entering the atmosphere, reducing greenhouse gas emissions, and may be referred to as carbon capture and sequestration (CCS), carbon geologic sequestration, or carbon geosequestration. Subsurface injection of CO₂ into gas or oil fields can also serve to displace remaining reserves out of the formation, in a process known as enhanced oil recovery and enhanced gas recovery (EOR and EGR, respectively). The double benefit of limiting emissions and increasing product yields makes the sequestration of CO₂ more attractive to major emissions sources such as oil and gas producers, and finds use at over 70 sites worldwide (Asghari and Al-Dliwe, 2005; Tian et al., 2005).

1.1. Monitoring a sequestration project

For a carbon geosequestration project to be effective, it must prevent the release of injected CO₂ into the surroundings and atmosphere. However, it is unrealistic to expect sequestration projects to be perfectly sealed, so acceptable levels of leakage must be established. Estimates give a seepage rate of around 0.01–0.1% per year for sequestration projects as an acceptable amount while maintaining an effective and meaningful carbon storage program (Etheridge et al., 2005; Hepple and Benson, 2005).

In order to maximize the value of carbon sequestration and meet retention goals, it is important to establish a monitoring program that can quickly detect and quantify a leak. Estimation of the total leaked volume is necessary for calculating the efficacy of storage

and to ensure it meets an established acceptable seepage rate, or is terminated. Jensen et al. (2009) describe a decision support system for hazardous waste sites that would be easily modified to apply to carbon sequestration. This system includes establishing a baseline database, a monitoring component that searches for changes, a risk system that determines whether a detected change represents a threat, and a response component that helps mitigate any negative impact (Jensen et al., 2009). Such framework is easily convertible to a monitoring program for a sequestration project, and emphasizes the role that detection technologies play in establishing and monitoring safe sequestration activities.

Monitoring of a sequestration project can be accomplished by many techniques including: underground measurements like well pressure monitoring, seismic detection, and predictive modeling of the injected plume in the subsurface; detection at the near surface through gas sampling; and at- or above-surface remote sensing methods for detecting CO₂ leakage. Each offers unique strengths, and a robust monitoring program should likely include elements from subsurface techniques such as seismic monitoring (Dodds et al., 2009), surface methods such as soil gas measurements (National Energy Technology Laboratory [NETL], 2012; Seto and McRae, 2011), and remote techniques (Zahid et al., 2011).

1.2. Structure of the review

This review focuses on at- and above-surface remote sensing technologies and methodologies that are applicable for monitoring a carbon geologic sequestration project. The terms “direct methods” and “indirect methods” are used within this review to refer specifically to the target of a remote sensor: either “direct” detection of emitted gases, or “indirect” proxy detection of environmental responses to escaped gases. Direct detection in the context of this review should not be confused with physical sampling methods, which might otherwise be classified as “direct” methods. Section 2 provides a brief justification for remote sensing tools in monitoring sequestration projects. Leak detection via indirect remote sensing methods is described in Section 3, followed by direct detection of escaped gases by remote sensing in Section 4. A review of the benefits and limitations of these methods is presented in Section 5, along with conclusions for establishing a meaningful leak monitoring program for the geologic sequestration of carbon dioxide.

2. Utility of remote sensing for CO₂ storage

2.1. Applications of remote sensing in carbon sequestration projects

Remote sensing is useful for many crucial parts of establishing and running a carbon sequestration project. Before any injection of CO₂ to the subsurface occurs, the site must first be characterized for viability as a storage location, including ensuring that there is limited or predictable movement of any injected materials, and little to no risk of leakage from storage (Benson and Cook, 2005). Remote sensing can be utilized in this respect, helping to identify fractures and faults that may serve as leakage pathways by detecting emissions of deep Earth gasses using differential absorption lidar (see Section 4.2.1), or by cataloging existing wells using magnetometers (Wells et al., 2006). Following preliminary site assessment, remote sensing is poised to play a major role in site

monitoring and leak detection; these applications are discussed in greater depth in the following sections.

A longtime concern regarding the use of remote sensors is their cost relative to traditional sampling measurements (United States Environmental Protection Agency [EPA], 2011). This is particularly true for satellite sensors, which are associated with very high development costs as well as risk that the launch may fail. Such was the case with the original Orbiting Carbon Observatory, which had the potential to monitor large-source carbon emitters with low uncertainty, but failed upon launch (National Research Council [NRC], 2009). However, sensor costs have generally decreased, making high quality remotely sensed data more accessible (EPA, 2011). Additionally, it is very unlikely that managers of a sequestration project will commission unique satellite sensors for their specific project, but will more likely rely on an existing sensor operated by commercial or government entities, defraying development costs and risks to these outside vendors (Birk et al., 2003; Mumby et al., 1999). Select existing and proven remote sensing technologies applicable to their specific needs and budgets will allow site managers to keep costs and risks of using remote sensing technology at an acceptable level (Benson et al., 2004).

2.2. Remote sensing vs. direct sampling methods

Remote sensing differs from direct sampling measurements by not requiring intrusive sampling methods, being more readily deployed in a mobile capacity such as an aerial or space-borne platform to survey broad swaths of a sequestration project in a short amount of time, and typically requiring minimal or zero onsite installation and labor (EPA, 2011; NETL, 2012).

The platform that a sensor is deployed upon will affect the capabilities of the sensor. Ground, aerial, and satellite deployments all have benefits and drawbacks that determine the suitability of a particular sensor for carbon geosequestration project monitoring (NETL, 2012). Ground sensors, due to their proximity to the target of detection, will provide higher resolution data and can provide continuous monitoring of a site. However, their spatial coverage is limited, requiring a network of sensors to fully monitor a geosequestration location (Flesch et al., 2004). Aerial and satellite platforms for sensors greatly increase the survey area of a single sensor, and may be contracted out, eliminating some maintenance and costs that may be associated with a network of on-site direct sensors (Saripalli et al., 2006; Seto and McRae, 2011). However, continuous monitoring is less practical, especially for aerial platforms. Further advantages and disadvantages are presented in Table 1.

3. Indirect methods of monitoring CO₂ geologic storage

Indirect remote sensing methods for detection of leaking CO₂ associated with geologic carbon sequestration are those methods that do not attempt to look at atmospheric concentrations of emitted gases, but instead use a proxy environmental response that has a detectable relationship with carbon dioxide leakage (Benson and Myer, 2002). Primary detection methods in this category are remote sensing for temperature, surface deformation, and vegetative stress.

3.1. Temperature anomalies

Remote sensing of temperature gradients and anomalies is useful for detection of CO₂ seepage when the leak causes a change in temperature relative to the surroundings (Bateson et al., 2008). A thermal difference may be a result of rushing gases causing localized freezing or escaping heated gases causing warming, which can be detected via a thermal imager (Fig. 1, Bateson et al., 2008; NETL, 2012; Wimmer et al., 2011).

Fig. 1. ATM thermal image showing high temperature areas around known gas vents in Latera, Italy (circled).

From Bateson et al. (2008).

In one instance, a known leak was surveyed using a ground-based Infrared Solutions IR Snapshot thermal imaging camera, and it was discovered that escaping gas was causing a localized air temperature decrease of up to 28 °C from ambient, detectable up to 5.5 m from the leak source (Wimmer et al., 2011). Thermal response can also be detected in plants subjected to higher levels of CO₂ concentration. Plants that are exposed to higher levels of CO₂ respond by reducing the rate of gas and water transport and exchange, resulting in a temperature increase within the plant of up to 5 °C detected via an aerial thermal infrared sensor, but not evident in standard aerial photography (Stohr et al., 2010). These sensors rely on a difference between the temperature of the detection target and its surroundings, so in circumstances where there is no thermal difference, a leak would go undetected (Bogue, 2003). Other potential issues include differential canopy heating and shading effects, which could mask temperature fluxes and provide false results (Leinonen and Jones, 2004). Also, in cases where the spatial resolution of a sensor is low, a localized temperature difference may be missed. Table 2 highlights strengths and weaknesses of thermal detection methods.

3.2. Surface deformation

Indirect detection of leaks in a geologic sequestration project can also be achieved via monitoring ground surface deformation. The principle behind such detection is that as CO₂ is injected to the subsurface at a constant rate, the ground will displace and swell in a consistent fashion (Benson and Cook, 2005; Benson and Myer, 2002). In the event of a leak to the system, this swelling of the surface might change to occur at a different rate, or even become a reversal from ground swelling to deflation (Rohmer and Raucoules, 2012).

Interferometry is high resolution, repeat-pass mapping of the ground surface elevation, and is useful for sensitive millimeter-scale change detection at sequestration sites (Crosetto et al., 2010; Onuma and Ohkawa, 2009). Comparing the surface at one time against the same location at a different time point, changes in surface elevation indicate changes in the subsurface due to injection. At the In Salah gas field in Algeria, interferometry products from the

Table 1 Comparison of deployment platforms for remote sensing methods useful in monitoring a CO₂ geologic sequestration site.

Deployment and Platforms	Advantages	Disadvantages	References
<i>Ground</i> LI-COR Instruments Boreal Laser Inc. GasFinder ASD Inc. FieldsSpec Pro	Continuous site measurements High spatial resolution Sensitive plume mapping of chemical species with minimal mixing effects	Low spatial coverage, likely require a network of sensors Sensors more exposed to environment, requiring maintenance	Flesch et al. (2004) Male et al. (2010) Detto et al. (2011)
<i>Aerial</i> AVIRIS ArgonST (Daedalus) 1268 ATM Specim AisaEAGLE HyVista HyMap	Rapidly deployed for an incident Relatively high spatial resolution with good area coverage Contracting eliminates maintenance by the sequestration team	Subject to weather and flight constraints Non-continuous monitoring Gas concentration detection subject to atmospheric mixing Expensive	Bateson et al. (2008) Bellante et al. (2013) NETL (2012) Martini and Silver (2002)
<i>Satellite</i> Landsat TM/ETM+ GOSAT TerraSAR-X NASA Aqua/Terra	Provides continent- and global-scale coverage Semi-continuous monitoring Relatively high spatial resolutions available Little to no need for maintenance	Lower resolution sensors make source identification difficult Concentration detection is strongly affected by atmospheric mixing, especially for small leaks Custom deployment is expensive and difficult	Crosetto et al. (2010) Onuma and Ohkawa (2009) Pickles and Cover (2004)

Table 2 Thermal methods for monitoring a CO₂ sequestration project for leaks.

Example technology and platforms	Advantages	Disadvantages	References
Thermal IR bands of spectral sensors including MASTER GasCam ArgonST (Daedalus) 1268 ATM	Detections will be associated with leak source Vegetative thermal response may allow 4 h detection	Sensitive to environmental conditions Thermal differential between gas and surroundings required No precise measures of concentrations or leak rates Requires high spatial resolution to detect thermal signal before too diffuse. Vegetative response subject to external factors	NETL (2012) Bateson et al. (2008) Bogue (2003) Etheridge et al. (2005) Stohr et al. (2010)

Envisat SAR system have been used to map surface deformations in the vicinity of injection wells (Fig. 2, Onuma and Ohkawa, 2009), measuring the rate of change at 5 mm per year, which is in agreement with subsurface plume modeling estimates (Ringrose et al., 2009; Vasco et al., 2010). An issue with detection via ground surface deformation is that the ground surface response may be over a broad area so the leak location or number of leaks would be difficult to determine from interferometry alone (Fielding et al., 1998). Furthermore, deformation methods are less reliable in complex or vegetated terrain, potentially causing a leak to go undetected (Table 3).

3.3. Vegetative stress

An indirect method that reveals more precise locations of leak sources than surface deformation is mapping vegetative stress. The principle behind vegetative stress monitoring for carbon capture and sequestration is that an overabundance of CO₂ will negatively affect plant health. Multiple studies investigating seepages of deep-earth hydrocarbon gases provide proof of concept that there is a detectable vegetative response associated with gas influxes to the soil, indicating the viability of such detection for a carbon

sequestration project (Noomen et al., 2008, 2012). It is hypothesized that excess CO₂ in the subsurface displaces other essential gases, causing the plant to die (Fitter et al., 1995; Sorey et al., 2000). Alternatively, the preponderance of CO₂ will cause a plant to close its stomatal openings (as with the thermal response), resulting in a complete shutdown of plant transpiration with consistent high CO₂ concentrations (Field et al., 1995). A compelling example of the effects of CO₂ leaks into the soil occurs at Mammoth Mountain, California, where subsurface volcanogenic CO₂ has resulted in complete vegetation die-offs (Martini and Silver, 2002).

There have been extensive efforts to study the response of plants subject to CO₂ stress to determine its applicability to the detection of carbon geologic sequestration leakages (Pickles and Cover, 2004; Spangler et al., 2010). Spectral methods are most commonly used, as the decline in plant health is accompanied by plant chlorophyll absorbing less radiation in visible wavelengths and reflecting less energy at near infrared wavelengths, creating an identifiable spectral signature (Bellante et al., 2013; Rouse et al., 2010). One such effort used volcanic vents as proxies for a leaking sequestration project, and attempted detection of the location of active vents using multiple spectral sensors (Bateson et al., 2008). Identification of leak source location was possible, but the highest successful

Table 3 Surface deformation methods for monitoring a CO₂ sequestration project for leaks.

Example technology and platforms	Advantages	Disadvantages	References
Radar interferometry including ENVISAT ASAR (defunct) TerraSAR-X ERS-1/ERS-2 SAR	High resolution of detection, on the scale of millimeters elevation change Detection unhampered by weather and time of day	Low accuracy in source detection Weak in complex terrain or heavily vegetated areas	Onuma and Ohkawa (2009) Fielding et al. (1998) Vasco et al. (2010) Rohmer and Raucoules (2012)

Fig. 2. Interferometric SAR image captured by the ENVISAT ASAR sensor, showing surface deformation rates at the In Salah CO₂ sequestration facility, Algeria. From Onuma and Ohkawa (2009). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

detection rate was 47% of known vents, as well as several false positives. Other studies on the effects of CO₂ leaks on plant health have been performed using ground-based FieldSpec Pro and air-based Pika II spectrometric sensors on an artificial subsurface CO₂ injection system at the Zero Emissions Research and Technology (ZERT) site (Male et al., 2010; Rouse et al., 2010). All found that in the area of a leak, seepage rates of >200 kg CO₂ per day resulted in detectable stress in surrounding vegetation, with decreasing vegetative stress at increasing distances (Fig. 3, Male et al., 2010). A recent study examined the use of a narrowband airborne sensor to map vegetative responses to artificially increased subsurface CO₂ at this test site, using a Red Edge Index (REI) that highlights spectral differences between unstressed, low, moderate, and highly stressed vegetation at the transition zone from visible red to near infrared wavelengths and showing promise for discriminating CO₂ subsurface leaks (Bellante et al., 2013).

A benefit of indirect detection of seepage via remote sensing of plant health is that the limited area out to which a leak has an effect on the vegetation serves to highlight a more discrete location to investigate for the source of the leak (Table 4). Causes for concern with remote sensing of vegetative stress include a lack of knowledge of the effect the size of a leak has on the response of vegetation (Amthor, 1995; Bellante et al., 2013), as well as how to distinguish spectral responses due to external influences on plant health such as weather or season from a response due to a leak (Pickles and Cover, 2004). It has been demonstrated that a detectable difference in stress response timing can be found between plants stressed by increased CO₂ levels as compared with plants stressed by herbicide application (Yahaya et al., 2011). Further study is needed to

characterize vegetative response to varying rates of carbon dioxide leak and distinguish the response from external stressors.

4. Direct methods of monitoring CO₂ geologic storage

Direct remote sensing methods for detection of CO₂ leaking from geologic sequestration projects attempt to analyze the gases emitted from a leak, such as CO₂ or tracer molecules, rather than looking for surrogate environmental responses (Benson and Cook, 2005). Detection of such chemicals in concentrations above baseline levels serve as an indicator that there is potentially a leak. This can be accomplished by passive sensor spectroscopic methods including hyperspectral sensors and IR sensors, as well as active sensors including laser based detectors (NETL, 2012).

4.1. Passive sensor methods for direct detection

Active and passive sensor spectroscopic techniques for detecting CO₂ presence operate on the same basic principle. Electromagnetic signals are detected by the sensor, and the received signals show varying levels of absorption or attenuation due to objects in the path of the signal (Benson and Myer, 2002). An area in the spectrum where the target chemical interacts with the signal is identified and the magnitude of change relates to the amount present to interact with the signal. The main difference between active and passive systems is that passive systems rely on ambient electromagnetic radiation, usually solar energy, while active systems produce their own (Abshire et al., 2010a).

Table 4
Vegetative response methods for monitoring a CO₂ sequestration project for leaks.

Example technology and platforms	Advantages	Disadvantages	References
Spectral sensors and vegetative indices including AVIRIS Quickbird Fieldspec FR Landsat TM/ETM+	Response gradient indicates proximity to leak source and leak concentration Short and long term monitor Many existing sensors and deployment platforms	Plant response subject to external stressors and factors Requires vegetation signature baseline Plant response signature detection may take 44 days	Amthor (1995) Pickles and Cover (2004) Yahaya et al. (2011) Rouse et al. (2010) Male et al. (2010)

Fig. 3. Classified image derived from a Resonon Inc. aerial hyperspectral sensor of vegetative stress due to artificially increased subsurface CO₂ at the ZERT test site in Montana. From [Male et al. \(2010\)](#). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

[Green \(2001\)](#) provided proof of concept for the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) passive hyperspectral remote sensing platform for detection of target species within an atmospheric column, demonstrating that by extending the path length of the signal (by varying the plane's height above ground) higher concentrations of carbon dioxide were detected with 1.3% precision. [Fig. 4 \(Spinetti et al., 2008\)](#) provides an example image from the AVIRIS sensor and associated plume map. Another passive sensor tested was the GOSAT satellite, a Japanese Earth observing satellite dedicated to monitoring greenhouse gasses, which was found to have fairly low retrieval precision around 30% ([Reuter et al., 2012](#)).

There are significant issues with the use of passive remote sensing methods for determining concentrations of CO₂ in the atmosphere ([Menzies et al., 2001](#)). These include uncertainties caused by temperature and weather variations in the atmosphere as well as window of opportunity constraints ([Table 5](#)). Additionally, long path lengths for aerial and satellite sensors result in the signal passing through high volumes of atmospheric CO₂, meaning CO₂ emitted from a sequestration leak is likely to be obscured unless at very high concentrations ([Benson and Myer, 2002](#)). Active sensing methods provide some refinement over passive techniques.

4.2. Active sensor methods for leak detection

Active sensors can be either open-path or closed-path ([Järvi et al., 2009](#)). Open path techniques are preferred because they typically require less maintenance, making them ideal for remote monitoring of carbon sequestration sites ([Detto et al., 2011](#); [Haslwanter et al., 2009](#)). Three promising open-path active sensing techniques for monitoring sequestration are differential absorption lidar (DIAL), Fourier Transform Infrared (FTIR), and Tunable Diode

Fig. 4. Map and image of volcanogenic CO₂ plume captured by AVIRIS hyperspectral sensor over Mount Kilauea in Hawaii. From [Spinetti et al. \(2008\)](#). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 5CO₂ direct detection methods for monitoring a CO₂ sequestration project for leaks.

Example technology and platforms	Advantages	Disadvantages	References
CO ₂ detection methods FTIR TDL DIAL Sensors including AVIRIS GOSAT LI-COR 7500	Directly detecting target species rather than a proxy Provides estimates of leak volume and concentration Flux models allow mapping of concentration plume	Difficult to discriminate CO ₂ signal due to leak vs. other sources and within atmosphere Spectral overlap obscures signal from leak Sensitive to environmental conditions and requires separate environmental measurements for calibration Subject to interference from water vapor, dust and aerosols	Benson and Cook (2005) Green (2001) Abshire et al. (2010a,b) Ehret et al. (2008) Etheridge et al. (2005) Menzies et al. (2001) Madsen et al. (2009) Jones et al. (2011)

Lasers (TDL). Their strengths and weaknesses are described below and in Table 6.

4.2.1. Differential absorption lidar

DIAL sensors send out a paired laser signal and compute concentrations by the difference in absorption levels and returns from the paired signal, one beam of which matches the absorption spectrum of the target species, the other of which does not (Browell, 1989). Several ground and air-based platforms have shown good detection of CO₂ (Fessenden et al., 2010; Reuter et al., 2012; Zéninari et al., 2004). Abshire et al. (2010a) demonstrated an experimental airborne lidar instrument that detected CO₂ concentrations in the air column to within 2.5% accuracy of concurrent physical samples. Modeling has shown great promise for spaceborne systems, with suggestions that CO₂ could be detected with only a 0.2% random error (Ehret et al., 2008; Menzies et al., 2001). Detection of 0.1 ppm differences have been demonstrated for low spatial resolution (111 km × 111 km) aerial sensors (Abshire et al., 2010b). However, at such low resolution, additional detection methods are necessary to determine the leak location.

4.2.2. Open Path Fourier Transform Infrared

Open Path Fourier Transform Infrared (OPFTIR) sensors allow for scanning of many different wavelengths simultaneously (as

opposed to DIAL instruments examining a single wavelength at a time), and are found to perform well in outdoor settings (EPA, 2011). Studies in laboratory conditions show high accuracy for OPFTIR sensors in detecting concentrations along a plume for common gasses such as CO₂, CH₄, and CO (Smith et al., 2010). However, the broadband nature of FTIR means it may be more prone to interference when scanning species such as CO₂ (Schiff et al., 1994).

4.2.3. Open Path Tunable Diode Laser

Open Path Tunable Diode Laser (OPTDL) sensors are able to scan very discrete, selectable wavelengths, meaning they detect only a single target chemical species, similar to a DIAL instrument but without the requirement of a paired signal (EPA, 2011). While an OPTDL system is not able to scan for many different compounds at once like an OPFTIR sensor, its tunability allows for more precision in detecting a specific absorption band, and therefore a specific compound. This may lead to higher detection sensitivity and longer acceptable path lengths (EPA, 2011; Schiff et al., 1994). Real world tests showed similar high accuracy in detecting emissions using OPTDL and OPFTIR methods (Ro et al., 2011). Both have the potential for long path lengths around 1 km, and do not require a large network of sensors and reflectors over this distance to provide useful data (EPA, 2011; Ro et al., 2011).

Table 6 Comparison of techniques useful for direct detection of escaped gases from CO₂ geologic sequestration projects (adapted from EPA 2011).

Active technology	Description of technique	Advantages	Disadvantages
Differential absorption lidar (DIAL)	Sends a paired laser signal, one strongly absorbed by the target, the other just outside of the absorption spectrum of the target. Differences in absorption between the returned signals identify the concentrations of the target species in the atmosphere	Long reported path lengths (3 km) No need for retro-reflectors Provides plume mapping abilities from concentrations along signal path Highly mobile instrumentation	Only detects a single species/compound at a time Only species with absorption bands are detectable, otherwise a class of species is detected Requires backscatter from aerosols or similar atmospheric particles High variable depending on environmental conditions of weather and temperature Expensive systems and limited access
Fourier Transform Infrared (FTIR)	Emits a broader-spectrum IR beam than laser-based sensors. Absorption is calculated from a Fourier transform algorithm applied to the returning IR beam to discriminate concentrations of various species in the path	Relatively cheap Able to detect multiple compounds at once Large number of detectable compounds within sensor's range	Spectral interference for key compounds in IR range Limited path length Plume flux calculations can be difficult Complicated setup and deployment
Tunable Diode Laser (TDL)	Utilizes a laser with fine spectral resolution, isolating a very specific wavelength for a target species. Detected absorption provides information about the levels of the target species in the sensor path.	High specificity allows for high measurement accuracy, low interference Long path lengths (1 km) Easy setup and deployment Cheap equipment costs	Only detects a single species/compound at a time Limited number of compounds able to be detected Limited sensitivity of detection

Table 7 Tracer direct detection methods for monitoring a CO₂ sequestration project for leaks.

Example technology and platforms	Advantages	Disadvantages	References
Tracer detection methods FTIR TDL DIAL Sensors including AVIRIS GOSAT LI-COR 7500	Detection known to be associated directly with sequestration project Provides a unique concentration signature Less spectral overlap with common atmospheric species Tracers are more likely to be detectable at very low concentrations	Subsurface reactions may cause an alteration of the composition and concentration of tracers Injected tracers may be more hazardous or more potent GHGs than CO ₂ Sensors may be sensitive to environmental conditions and require separate environmental measurements for calibration Subject to interference from water vapor, dust and aerosols	Benson and Myer (2002) Klusman (2011) Leuning et al. (2008) Wells et al. (2006) Etheridge et al. (2011) Madsen et al. (2009) Jones et al. (2011)

Table 8 Technological readiness levels of remote-sensing-based monitoring methods for monitoring a CO₂ sequestration project for leaks.

Remote monitoring method	Sensor availability	Readiness level	References
Thermal anomalies	Commercially available sensors include: ArgonST 1268 ATM Infrared Solutions Snapshot Series	Limited testing at enhanced oil recovery sites with success	Bateson et al. (2008) Stohr et al. (2010) Wimmer et al. (2011)
Surface deformation	Satellite sensors include: TerraSAR-X Envisat ASAR (no longer operating)	Successfully utilized as part of the monitoring program at the In Salah, Algeria carbon sequestration project	Onuma and Ohkawa (2009) Rohmer and Raucoules (2012)
Vegetative stress	Commercially available sensors include: Specim Aisa Series ASD FieldSpec Pro	Commercially available and tested with promising results in experimental conditions. However, limited deployment in non-experimental settings	Bateson et al., 2008 Male et al. (2010) NETL (2012)
Gas detection	Commercial sensors include: LI-COR LI-7500 Boreal Laser GasFinder Series	Tested at experimental sequestration sites and at In Salah, Algeria sequestration project, but without conclusive results due to disadvantages listed in Tables 5 and 7	Madsen et al. (2009) Jones et al. (2011) NETL (2012)

4.3. Tracer methods

The most direct method of identifying a leak in a carbon geologic repository would be to detect an elevated presence of CO₂ in the local atmosphere. However, it can be difficult with any of the aforementioned techniques to detect a clear CO₂ signature due to CO₂'s abundance in the atmosphere, variability within the air column, and genesis from many natural and anthropogenic sources (Benson and Cook, 2005; Klusman, 2011). It can be useful to instead detect chemical tracers naturally present or added with any injected CO₂ (Leuning et al., 2008; Saripalli et al., 2006). These are molecules that occur with low, relatively constant concentrations in the environment and may have absorption spectra more easily detected by such tools as OPFTIR and OPTDL (Wells et al., 2006). Common tracers include noble gases, perfluorocarbons, methane, and carbon isotopologues (Klusman, 2011; Wells et al., 2006). Example tracer spectra are provided in Fig. 5 (Detto et al., 2011).

4.3.1. Non-additive tracers

Non-additive tracers such as isotopologues rely on prior knowledge of the ratios of the different carbon isotopes within the injected CO₂, so that the particular ratio can be used to distinguish from environmental CO₂. In regards to the remote sensing methods described above, ¹³CO₂ is the most likely candidate for isotopologue detection (Reuter et al., 2012; Risk et al., 2013). Gases like methane and ethane naturally occur within some geologic sequestration sites, particularly those in depleted gas and oil fields, and exist at lower ambient concentrations, making them easier to detect than CO₂ (Klusman, 2011; White et al., 2010). Analysis has shown that for detection of CO₂ one standard deviation above baseline atmospheric levels would require a leak rate of 5.26 g per second, vs. 0.11 g per second for CH₄ used as a tracer (Klusman,

2011). Injection of CO₂ into formations carrying these gases displaces them, and increased concentrations at the surface would be evidence of a pathway through which gases are escaping (Wells et al., 2006).

4.3.1.1. Signal-to-noise ratio of non-additive tracers. A primary issue to be considered when using non-additive tracers, and particularly CO₂ isotopologue tracers, is the signal-to-noise ratio (SNR) for detecting a leak in comparison to background environmental carbon dioxide (Risk et al., 2013). Without a consistent SNR above a meaningful level (a 1:1 SNR value is effectively unusable), leak monitoring at a sequestration site will be severely hampered.

Fig. 5. Recorded spectra for emissions over a wetland in California using gas analyzers including the open-path LI-7700 and LI-7500 sensors. From Detto et al. (2011). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The most likely carbon dioxide isotopologues for tracer monitoring are the stable isotope $^{13}\text{CO}_2$ and the radioisotope $^{14}\text{CO}_2$. $^{14}\text{CO}_2$ is likely to have a strong SNR, with simulations estimating it at 100:1 for lower volume leaks than used in the ZERT experiments, but is not easily measurable by the described remote sensing methods (Nickerson and Risk, 2013; Leuning et al., 2008). $^{13}\text{CO}_2$ shows potential as a tracer, though with a weaker SNR than the radioisotopologue (Klusman, 2011; Nickerson and Risk, 2013), and existing and developing sensors including ground-based spectrometers and GOSAT may be able to detect $^{13}\text{CO}_2$ with some precision (Leuning et al., 2008; Reuter et al., 2012). Non-isotopic non-additive tracers are likely to have strong SNR values, as they would primarily be deep-earth gases with fewer environmental sources (Klusman, 2011).

4.3.2. Additive tracers

Additive tracers, including sulfur hexafluoride and noble gases such as xenon, can greatly enhance the ability to detect leaks when injected concurrently with sequestered CO_2 , and characteristically will have high signal-to-noise ratios (Klusman, 2011; Saripalli et al., 2006). At one test site, detection of injected perfluorocarbon tracers at levels of parts-per-quadrillion was used to demonstrate that the total leak rate of the system was roughly 0.0085% of sequestered CO_2 per year (Wells et al., 2006). However, additive tracers are commonly greenhouse gases with stronger per molecule effects than CO_2 (Leuning et al., 2008; Table 7). Other restrictive factors may include costs of the tracers and detectors, as well as community objection to usage of potentially hazardous chemicals (Klusman, 2011). However, these are still important tools to be considered for the monitoring of a sequestration project (Wells et al., 2006).

5. Conclusions

5.1. A robust monitoring approach

The remote sensing technologies reviewed are all useful means of monitoring a carbon dioxide geologic sequestration project for leaks. However, all these methods suffer in some ways that are likely to be an issue at a carbon sequestration site (Tables 2–7). Many spectroscopic methods suffer from absorption interference when attempting to detect CO_2 directly. Ground surface deformation detection may not provide a precise leak location, while temperature and vegetative stress detection are inviable if no change from baseline is present, or if changes are due to external factors.

For this reason, a robust monitoring program must utilize multiple detection methods suited to the specific project (Etheridge et al., 2005). Factors including site topography, climate, and ecosystems, as well as technological readiness levels must all be considered when selecting monitoring tools. Locations with frequent cloud cover would likely want to avoid passive-type aerial and satellite sensors, and open path sensors would not be well suited to sites with frequent snowfall or other particulates, which can obstruct the sensor beam (Menzies et al., 2001). As an example of remote sensing methods suited to the sequestration project conditions, a site with relatively simple surface topography and mild climate might utilize satellite interferometry to monitor for a shift in surface deformation rates, and upon leak detection, tracers could be injected and an OPTDL sensor used to find the precise location and rate. Similarly, combining thermal imaging and vegetative stress monitoring for a sequestration project with ample, non-complex vegetative coverage would provide the benefits of sensing changes in the health of plants and gas temperatures above a sequestration location, as well as providing further information from any thermal response by the vegetation in the event of a leak. On the

other hand, such detection combinations may prove useless at a sequestration site in highly complex terrain or without vegetative cover. Technological readiness level is another important consideration (Table 8). Utilizing a suite of only experimental sensors that have not been field validated would likely provide incomplete or inaccurate data, so it is advisable that a select few experimental technologies be deployed in conjunction with proven monitoring methods. Multiple sensor methods will serve as redundancies in a monitoring program, ensuring that if one method fails to detect a leak, another will not.

Monitoring programs should employ a combination of the remote sensing methods presented here, likely in conjunction with other monitoring methods such as using seismic tools to identify probable leak pathways like faults, then establishing remote sensing technologies around these features to detect escaping gases. Managers of any carbon geologic sequestration project will need to examine all available options and their readiness for deployment, then determine the suite of detection tools that will provide accurate monitoring in the most efficient and economical manner.

5.2. Summary and final thoughts

Monitoring of geologic carbon sequestration projects is necessary to ensure that such efforts are an effective means of limiting carbon dioxide emissions to the atmosphere. Loss of injected CO_2 volume greater than 0.1% per year may negate any benefits from carbon geosequestration, highlighting the need for quick and accurate leak detection (Saripalli et al., 2006). Monitoring by remote sensing provides large coverage and rapid detection without the need for invasive or disruptive installations (EPA, 2011). Applicable remote sensing methods for monitoring for leaks in carbon geologic sequestration include indirect methods that reveal environmental changes as well as methods that directly characterize emitted gases.

Different remote sensing methods have drawbacks including limited spatial resolution, detection precision, availability, coverage, and other factors, so further investigation and refinement of existing tools is necessary (EPA, 2011). However, they present important advantages over physical sampling methods that might otherwise be used to monitor a carbon sequestration installation. These devices and techniques can generate measurements aboard highly mobile devices, allowing for quick deployment surveying large extents (EPA, 2011). Particularly with airborne platforms such as the AVIRIS sensor or satellites such as TerraSAR-X, broad or even global coverage can be provided rapidly without the need for a large on-the-ground network of monitoring installations (Crosetto et al., 2010; Spinetti et al., 2008). This also reduces costs associated with purchasing multiple point monitoring units, maintaining them, and processing samples they collect (EPA, 2011; Seto and McRae, 2011), making carbon sequestration projects more cost effective (Zahid et al., 2011).

As nations and industries seek ways to mitigate greenhouse emissions, carbon capture and sequestration projects will become more prevalent as one of the most economical methods of achieving reductions (Global CCS Institute, 2013). Furthermore, as governments and agencies worldwide push for greater understanding of the environment and the effects of greenhouse emissions, new satellites and sensors are being deployed that will offer additional monitoring resources to sequestration projects. The European Space Agency (ESA) will begin its Sentinel series of satellites in 2014, starting with the Sentinel 1 which will offer interferometric deformation detection, followed by the Sentinel 2 satellite which carries a multispectral scanner useful for monitoring vegetative change (Aschbacher and Milagro-Pérez, 2012). NASA's relaunch of the Orbiting Carbon Observatory (OCO-2) will provide region-scale

identification of carbon hotspots (Boesch et al., 2011), potentially providing a preliminary monitor for larger sequestration projects. Current remote sensing technology can provide robust monitoring capabilities in many forms for a sequestration site, and continuing development of the field, especially when tied to experimental carbon storage projects expressly to advance monitoring methods for sequestration (Global CCS Institute, 2013), will yield additional methodologies with increased accuracy and decreased costs.

Future research should seek to identify alternative tracers that are not greenhouse gases and have little to no negative environmental impact of their own. Advancements in signal discrimination and detection of CO₂ or other chemicals associated with geologic sequestration are needed to enhance the utility of spectroscopic methods. Additionally, greater research into existing tools such as DIAL as deployed on aerial and satellite platforms will promote utilization of remote sensing methods and demonstrate the capabilities of such tools for larger coverage. Leak detection via remote sensing should serve as a primary tool in a portfolio of monitoring techniques in order for geologic sequestration of CO₂ to be a viable and economical method of regulating atmospheric emissions and abating climate change.

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