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Looking for leakage or monitoring for public assurance?

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Abstract

Monitoring is a regulatory requirement for all carbon dioxide capture and geological storage (CCS) projects to verify containment of injected carbon dioxide (CO_2) within a licensed geological storage complex. Carbon markets require CO_2 storage to be verified. The public wants assurances CCS projects will not cause any harm to themselves, the environment or other natural resources. In the unlikely event that CO_2 leaks from a storage complex, and into groundwater, to the surface, atmosphere or ocean, then monitoring methods will be required to locate, assess and quantify the leak, and to inform the community about the risks and impacts on health, safety and the environment. This paper considers strategies to improve the efficiency of monitoring the large surface area overlying onshore storage complexes. We provide a synthesis of findings from monitoring for CO_2 leakage at geological storage sites both natural and engineered, and from monitoring controlled releases of CO_2 at four shallow release facilities – ZERT (USA), Ginninderra (Australia), Ressacada (Brazil) and CO_2 field lab (Norway).

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Keywords: Monitoring; CCS; carbon dioxide; CO_2; geological storage; geosequestration; leakage; ZERT; Ginninderra; Ressacada; CO_2 field lab

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1. Introduction

Monitoring is a basic regulatory requirement for all carbon capture and storage (CCS) projects; to verify that injected carbon dioxide (CO_2) remains in its storage complex, and that there will be no threat to human health, or adverse environmental impacts. Carbon markets require storage to be verified, and the public wants assurances that they won't be impacted.

Regulators place a high priority on monitoring the storage complex in order to track the location and movement of injected CO_2 [1-4]. Similarly, stakeholders would like to know if CO_2 is escaping from the storage complex into the overburden, potentially contaminating overlying resources such as groundwater, oil and gas pools, or coal seams. In the unlikely event that the storage complex fails, and CO_2 leaks from the storage complex, through the overburden, and into the atmosphere or ocean, then monitoring methods will be expected to locate and monitor the leak, to quantify the leak, and to inform the community about the risks to health, safety and the environment. A CO_2 storage site includes a range of anthropogenic, geological and biological features which need to be monitored: from precisely positioned injection wells through complex geological systems, to the potentially large surface areas overlying a storage complex. This paper considers strategies to improve the efficiency of monitoring the large interface between the ground and atmosphere overlying the storage complex.

Surface monitoring methods, such as shallow groundwater monitoring, surface water monitoring, soil gas sampling, soil flux, and eddy covariance atmospheric monitoring, typically provide poor spatially resolution, are labour intensive, and often involving significant and complex data processing. Further, these activities may be required throughout the life of injection operations and many years after. These techniques have been routinely deployed at demonstration storage sites [5-6] for assurance monitoring, but their deployment is not necessarily commensurate with the risk of leakage at these sites.

Assurance surface monitoring contributes towards the social licence to operate a storage site, and is critical for addressing public concern around areas, or sites, with high social, economic or environment value, e.g. monitoring a particular stream, endangered plant community, basement in a house, or private groundwater well [7]. In this respect, assurance monitoring is quite specific, and by its nature, highly localized, as it seeks to demonstrate that there is no significant impact from a CO_2 storage project on features of interest, over many years. It appears likely that for larger projects, the scale of assurance surface monitoring undertaken at many pilot and demonstration sites today may not be viable on proportionally larger scales, over longer time frames.

Storage sites are selected on the basis that they are not likely to leak. It is therefore unlikely that resampling the same point location year on year, or the siting of continuous monitoring stations using soil flux, soil gas, eddy covariance or similar techniques around a geological storage site, will coincide with an actual leak [7]. Monitoring programs for future projects will need to be risk-based, and fit-for-purpose, based on consideration of the physical characteristics of the storage site, the risk profile of the storage site, the scale of the injection operations, the project uncertainties, and the potential for significant impacts. A risk-based program may be limited in scope to the higher risk features of a storage complex, and the conclusion that there is no environmental impact would be drawn if these impacts are ruled out at some agreed threshold or level of impact. This means that surface monitoring programs will require a component of continuous baseline and assurance monitoring, but will also require a contingency response program which has flexibility to respond to unforeseen changes in the risk profile of the storage site and surrounding region: to "scale-up" when a leak is detected, or suspected from subsurface monitoring. Current approaches to monitoring may not provide very specific spatial information about where monitoring should be conducted to find surface expressions of leaks. In this paper we seek to clarify how surface monitoring could proceed and what the limitations might be.

Nomenclature

Assurance monitoring refers to near surface monitoring performed to reassure stakeholders that assets such as groundwater wells are unaffected by storage operations and there is no threat to health and safety.
Leakage refers to unintended movement of CO_2 out of pre-defined containment.
Monitoring refers to measurement and surveillance activities necessary to provide an assurance of the integrity of CO_2 storage [4].
Storage complex refers to a subsurface geological system comprising a storage unit and primary and possibly secondary seals, extending laterally to the defined limits of the CO_2 storage operation or operations. Limits can be defined by natural geologic boundaries, regulation, or legal rights [4]
Storage site refers to a defined volume within a geological formation used for the geological storage of CO_2 and associated surface and injection facilities [8].

2. Leakage surface expression

Field experiments at CO_2 controlled release facilities, in different parts of the world, show that established near surface environmental monitoring techniques are effective for characterising "known leaks"; providing insights into near surface plume migration, impact on groundwater chemistry, mapping the lateral extent of a leak, and demonstrating CO_2 leakage quantification techniques [9-14]. Table 1 compares four controlled release sites where shallow CO_2 release experiments have been conducted through an undisturbed overburden, and where leakage has been detected at the surface. The four sites compared are Ginninderra (Canberra, Australia), ZERT (Bozeman, Montana, USA), RESSACADA (Florianopolis, Brazil), and the CO_2 Field Lab (Svelvik, Norway). The depths of injection vary between 1.2 to 20 m.

Table 1. Comparison of controlled release facility properties

Site	**Ginninderra**	**ZERT**	**RESSACADA**	**CO_2 Field Lab**
Location	Australia	US	Brazil	Norway
Depth of release (m)	2.0	1.2 – 2.5	8.0	20
Well orientation	horizontal	horizontal	vertical	45º inclined
Length of CO_2 release zone (m)	82	70	0.3	<1
CO_2 injection rate (kg/d)	144 - 288	100 - 300	2.2	120 - 420
Soil type	Buried fluvial	Alluvial deposits	Sand with some clay lenses	Sand
Vegetation cover	Canola, barley, wheat, field peas	Alfalfa, clover, dandelion, grasses	Grasses	Almost none
Typical groundwater level during release (m below ground)	0.85 – 2.3	1.5	1.5 – 2.0	0.8 – 1.2
CO_2 surface breakthrough (days)	<1	<1	~3	~1

All experiments show a similar type of leakage behaviour: that the surface expression of CO_2 leakage, even under highly controlled conditions, is restricted to localised hot spots. Leakage at these sites is not homogenous and evenly distributed over a wide area, but is characterised by small zones (1 – 10s of metres in diameter) of high CO_2 intensity that rapidly falls to background conditions away from the leakage zone (Fig. 1). The release experiments demonstrate that CO_2 will not necessarily express at the surface above the leakage point and there can be substantial lateral migration in the near subsurface (Fig. 1c and Fig. 1d). In the RESSACADA experiment, elevated surface CO_2 flux was observed some 30 m from the vertical release point at a surface depression next to a road. This corresponded with electrical resistivity measurements conducted at the site that tracked the migration and direction of the subsurface plume.

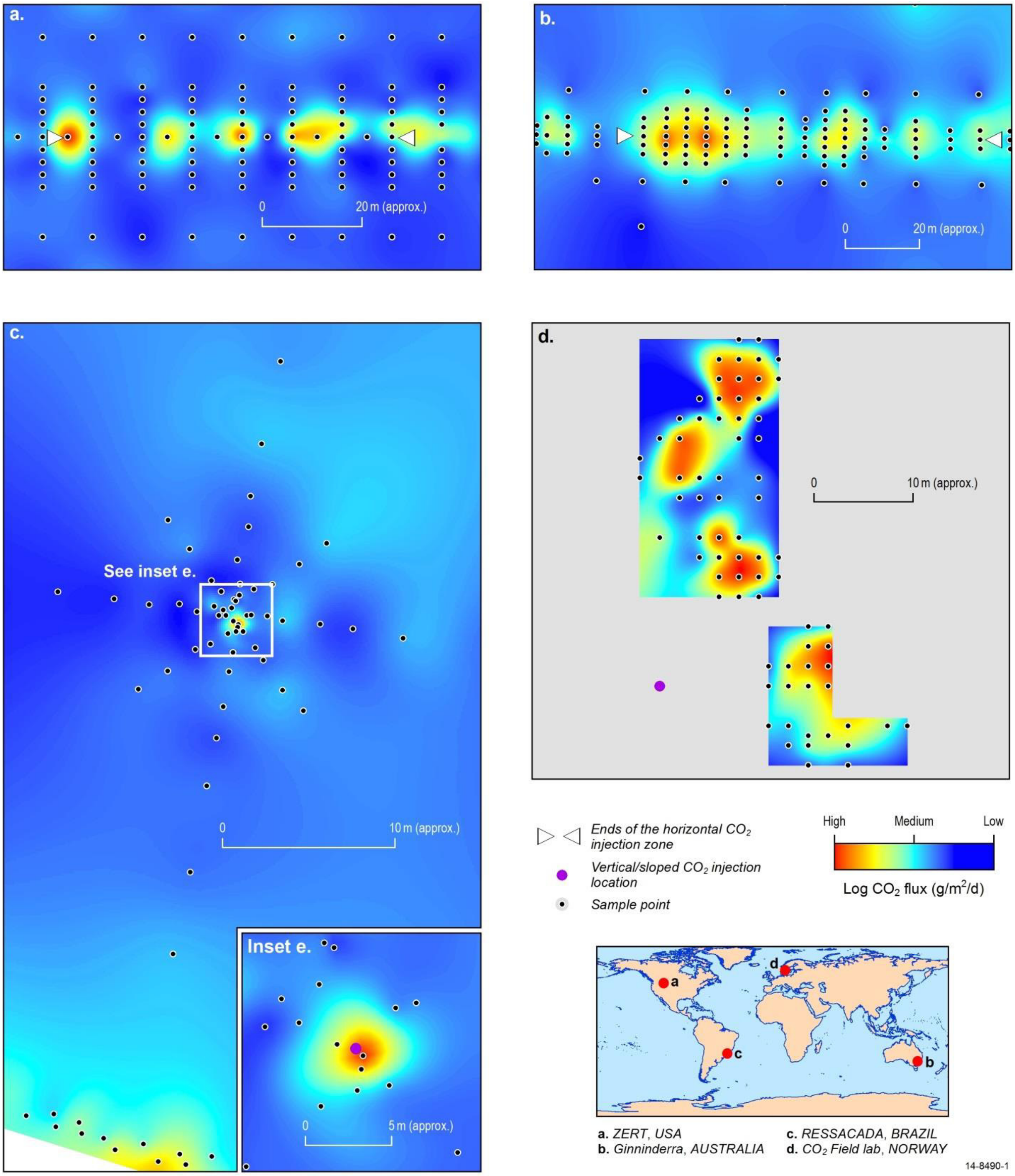

Fig. 1. Examples of soil CO_2 flux maps observed at controlled release sites and the location of the CO_2 release zones. Note that (a),(b) and (c) have been zoomed in from their original survey extent for clarity. The two white triangles in (a) and (b) indicate the extent of the horizontal well CO_2 release zone, which is continuous between these two points. Each site has different baseline and maximum flux values: log CO_2 flux for (a) ZERT (Bozeman, Montana, USA; high = 3.67; low = 1.22); (b) Ginninderra (Canberra, Australia; high = 2.94; low = 0.22);(c and e) RESSACADA (Florianopolis, Brazil; high = 2.66; low = 0.57); (d) CO_2 Field Lab (Svelvik, Norway; high = 2.11; low = -1.15).

One possibility for the observed CO_2 hot spots at the surface could be higher permeability streaks and relative weaknesses in the soil profile. Small variations in the soil properties could lead to preferential pathways. The opportunity to compare the behaviour at these small scale release experiments with larger leakages in the near surface from deep geological storage has not arisen, but results from natural leaks display similar "patchy" surface expression [16-24]. Since results from controlled releases and natural releases to date suggest that CO_2 leaks do take preferential pathways, it is important to examine the implications if a similar type of behaviour occurred during an actual leak from deep engineered storage.

3. High risk zones and broad-scale detection at the surface

Near surface monitoring programs should be informed using a risk-based approach, first surveying areas of higher risk such as operational and abandoned wells [25]. Human observation (e.g. bubbling through pooled water, audible hissing, vegetation die-off, salt scars) at wells and other infrastructure is important for the detection of small leaks and should be formally integrated into a regular maintenance program.

Although monitoring should be risk-based, prior information on the location of potential leaks is imprecise in the present state of knowledge. Broad-scale detection technologies such as airborne hyperspectral or mobile CO_2 sniffer type monitoring (ground-based or airborne) will be required to find small-scale seepage features, but this technology is the least well developed. Airborne methods offer two contrasting possibilities for surveying large areas cheaply. Sniffer drones, flying at altitudes of a few metres, may be able to get close enough to leaks for their CO_2 signal to stand out above background levels. Conventional aerial imagery can cover wide areas at reasonable cost but detection can be ambiguous at present.

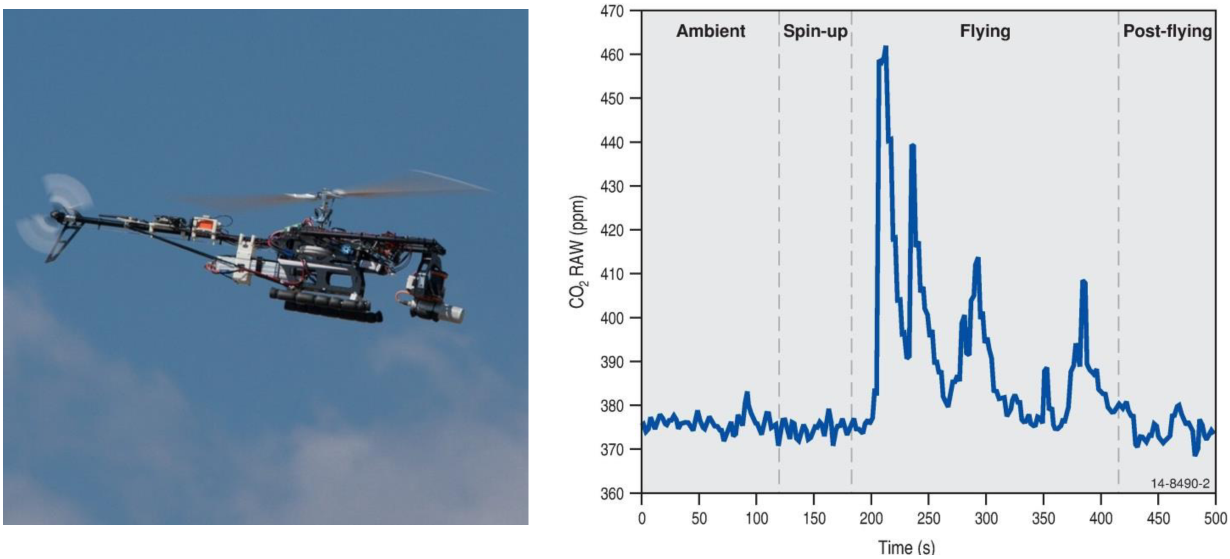

Fig. 2. Preliminary results of CO_2 detection using an unmanned aerial vehicle (UAV) for surface leak detection from Popp et al [28]. The photo of the left shows the UAV equipped with a Vaisala GMP 343 CO_2 sensor (sampling rate 0.5 Hz), which is located at the front of the battery powered vehicle. The figure on the right illustrates the CO_2 response of the sensor as the UAV criss-crosses at ~2 m height over a 100 kg/d surface release under continuous flight conditions. Photo by Uwe Zimmer (ANU).

If we consider firstly the detection of anomalous CO_2, promising results have been achieved using ground-based mobile detection systems at controlled release sites [26] and natural seepage sites [18]. Detection of small-scale CO_2 leaks using airborne systems is at an early stage of development but also shows promise [27,28]. An example is given in Figure 2 from Poppa et al [28]. CO_2 was released from a chamber on the ground at 100 kg/d and an UAV equipped with a Vaisala GMP 343 CO_2 sensor flew transects at 2 m height over the release point. The sampling was 0.5 Hz, which meant that the UAV had to fly relatively slowly, but it was possible to detect the small CO_2 leak under continuous flight conditions (Fig. 2). The perturbations from the release detected by the sensor were consistent with modeling of the leakage plume [29].

Progress on airborne sniffer technology appears to be limited by existing sensor technology and the absence of suitable small, precise, high frequency CO_2 sensors. Measurements must also be taken close to the ground surface in order to detect the signal [29]. A static network of atmospheric sensors has been demonstrated to detect leaks over a relatively large spatial area [30] but sensor performance and cost presently limits wider deployment. Scanning differential absorption lidar (DIAL) has also been investigated for CO_2 leak detection over 1 – 2.5 km scales [31].

Biological monitoring relies on detecting a vegetation stress response as plants are affected by increased CO_2 levels in their root zone. It is in its infancy in terms of its development, uptake and application to CO_2 storage projects [32], but has the potential to survey large areas at relatively low cost. One approach is to use airborne hyperspectral or multispectral imaging. This has been deployed at controlled release sites [33,34] and has been used with some success at natural CO_2 seeps [35-38]. Example hyperspectral images for ZERT and Ginninderra are provided in Figure 3. For the ZERT data (Fig. 3a), an unsupervised classification approach shows a high degree of spatial correlation between the hot spot locations identified using hyperspectral data in 2009 with hot spots previously identified using soil flux techniques in 2008 [38]. In the case of the Ginninderra data, conventional spectral indices have been found to delineate the damage to vegetation caused by CO_2 [14]. Figure 3c is an image obtained by forming a ratio of the reflectance at a wavelength of 1500 nm to that at 500 nm, and by comparison with Figure 3d, it can be seen that the region of leakage is detected. This index produces fewer false alarms than other choices but the region of leakage is clearly not uniquely identified.

Interpretation of the measurements is complicated by the changes in soil surface not due to CO_2 impacts such as cropping, ploughing, animal disturbances, drought, pests, or absence of vegetation, which create false positives. Application is also limited by winter snow cover. Nevertheless, when used in conjunction with aerial photography and with knowledge about the size and shape of an expected leak (i.e. 1-10 metre circle), this technique may be able to narrow the area for ground-based investigations using techniques such as soil gas, soil flux or near surface mobile atmospheric measurements. Evidently, site operators would want the false positive rate to be low as otherwise the technique could lead to numerous unnecessary investigations.

While searching for surface expressions of leakage may be difficult, there is likely to be relevant prior information e.g. indications of migration from deeper subsurface monitoring. This can be assimilated into a methodical and rational search strategy by the methods of Bayesian search theory [39]. This technique is used routinely by the US Coastguard, for instance, and yields a search that can be updated in real time on the basis of null results, and also optimised for finite amounts of time or other resources. Once a CO_2 leak is detected, conventional monitoring techniques such as soil gas, soil flux surveys and atmospheric techniques can be deployed to monitor leakage, characterise the extent of leakage, understand plume behaviour, and quantify the leak magnitude.

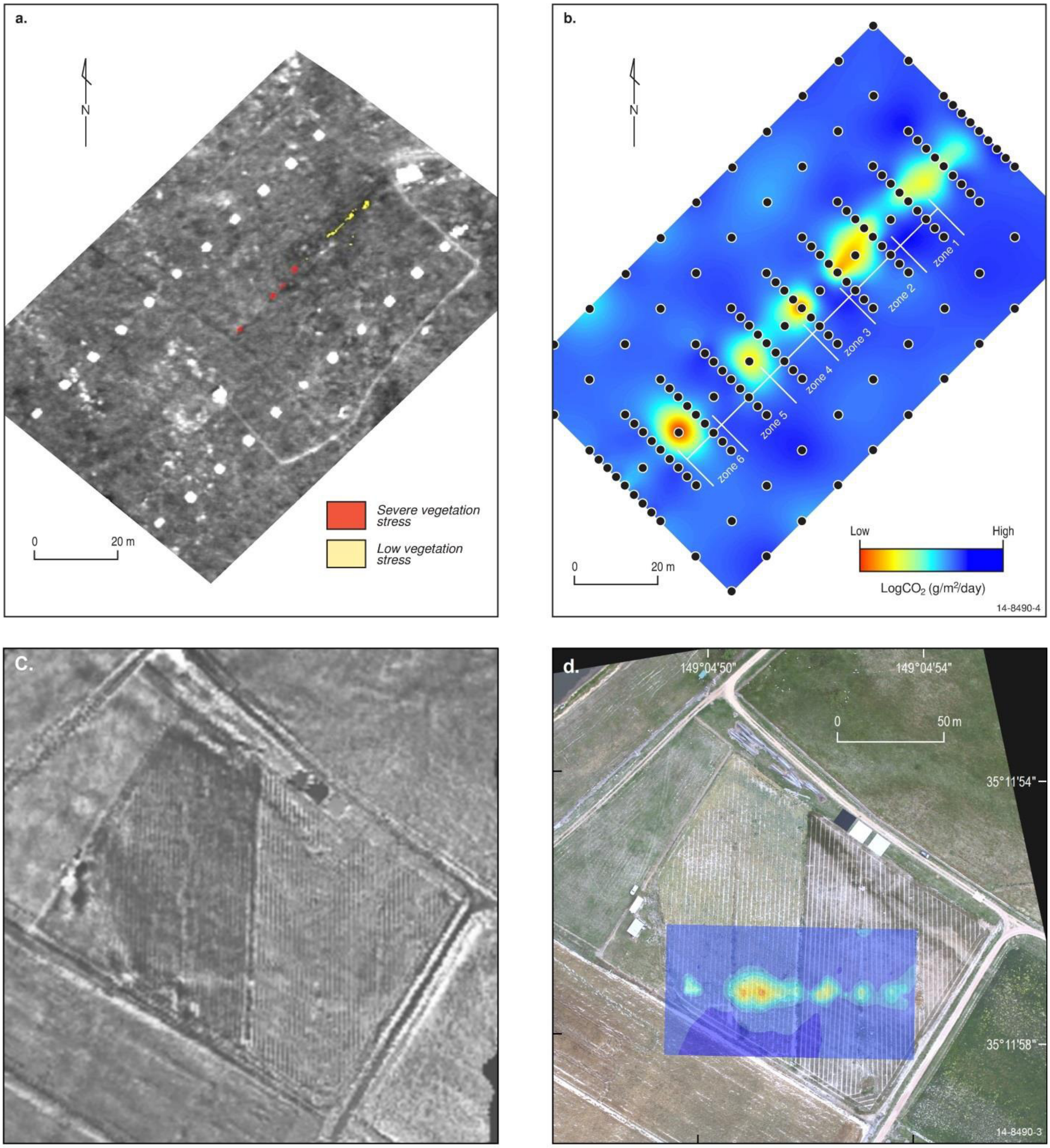

Fig. 3. Comparison of airborne hyperspectral measurements at (a) ZERT and (c) Ginninderra and comparison to soil flux maps for (b) ZERT and (d) Ginninderra. The ZERT hyperspectral image uses an unsupervised classification whereas measurements at the Ginninderra site are display using a ratio of the reflectance at 1500 nm to that at 500 nm. The ZERT illustration shows a high degree of spatial correlation of the hot spot locations between the June 25 unsupervised classification result (a) and a CO_2 flux map derived from accumulation chamber ground measurements made on July 30, 2008 at the black dots (b). Note that the unsupervised classification only included analysis of zones 1-3, whereas the flux map was derived during an injection into zones 1-6. For soil CO_2 flux scales, refer to Fig. 1.

4. Summary and recommendations

- Experiments from control release experiments show that surface leakage is not uniformly distributed, even under highly controlled conditions, but is localised and patchy, expressing as small (1-10s of metres in diameter) high intensity flux “hot spots”. This phenomenon is consistently observed at natural CO_2 seepage sites and controlled release studies. Moreover, the location of the surface expression can move depending on climatic conditions, most likely due to the influence of groundwater levels and the extent of the vadose zone.
- Biological surveys show promise as a low cost and effective method for detecting and locating leaks on a regional scale, but typically suffer from a high false positive rate. Surveys at control release sites have found that CO_2 impacts on plants can be clearly observed at ground level suggesting there is potential to improve airborne techniques.
- Airborne and ground-based mobile detection systems show promise as cost effective technologies for leakage detection over wider areas or even regional scales.
- Monitoring programs are likely to encompass multiple technologies with multiple purposes, objectives, regulatory requirements and technical designs. Monitoring programs should be customised for the characteristics, features, risk profile, uncertainties and regulatory requirements of specific storage sites and surrounding regions. This will require integrated monitoring programs that address potential impacts on all aspects of the environment within which the CCS project operates. The design of the monitoring program should be re-evaluated whenever the risk profile changes.
- There will always be financial pressures to achieve monitoring objectives at lowest cost. Open ended cost models increase uncertainty about project economics. For marginal projects like CO_2 storage, high levels of uncertainty will have a negative impact on project viability.
- Combinations of technologies that compliment, and verify the findings of the other, should be encouraged, rather than relying on single technologies, particularly in the early stages of a project when uncertainties around risk are highest.
- Models of the physical, chemical and biological processes at the storage site will need to be developed to aid in the interpretation and understanding of the monitoring results. For each monitoring program, the thresholds that indicate a potential leak will need to be determined, for each type of instrument deployed, and for each parameter measured, at each site [32].

5. Conclusion

To answer the question posed by the title: what is the purpose of near surface monitoring? Is it looking for leakage or monitoring for public assurance? Geological storage projects will need a social licence to operate. Public concerns about leakage therefore need to be addressed, regardless of whether or not geological risk assessments conclude that the likelihood of leakage is insignificant. Therefore, a basic level of surface monitoring will always be required for assurance purposes. A practical near-surface monitoring approach will initially focus on potential leakage pathways with some elevated probability of occurrence (e.g. wells), or receptors that have higher consequence (e.g., basements of occupied buildings). This provides assurance to individuals, the public, regulators, carbon markets and other stakeholders, that the storage site is performing as originally intended. However, this needs to be complemented with cost-effective techniques that can monitor for small-scale leak features over wide areas. In the unlikely event that monitoring indicates that CO_2 is escaping from a storage site into the atmosphere, surface monitoring will be fundamental in locating, assessing, and quantifying the leak. Research continues, through a world-wide network of control release facilities, to find the most cost effective approaches for assurance monitoring and for leakage detection and assessment.

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