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Environmental impacts of CO_2 leakage: recent results from the ASGARD facility, UK

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Abstract

The RISCS (Research into Impacts and Safety in Carbon Storage) project is investigating potential environmental impacts of CO_2 leakage. At ASGARD (Artificial Soil Gassing and Response Detection), a fully-replicated facility for controlled injection of CO_2 into soil, investigations have been carried out to determine the effects of elevated soil CO_2 on crops, soil microbiology, soil flux and soil CO_2 concentration.

Keywords; CO_2 storage, ASGARD, crop stress, CO_2 flux, microbiology

1. Introduction

Carbon Capture and Storage is increasingly seen as a way of combating rising CO_2 concentrations in the atmosphere. Although storage sites will be designed for zero leakage it is important to consider the possible environmental effects in the unlikely event that leakage does occur, for both risk and environmental impact assessments. The potential responses of ecosystems depend on CO_2 concentrations, event duration, the sensitivities of different organisms and external environmental factors [1]. The RISCS (Research into Impacts and Safety in Carbon Storage) project is investigating these issues using the

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University of Nottingham ASGARD (Artificial Soil Gassing and Response Detection) facility. ASGARD applies controlled injection of CO_2 into soil to measure the impacts on crop species of diffuse CO_2 leakage over periods of several weeks to months. The system design is fully replicated and enables monitoring of changes in plant and soil conditions and the testing of CO_2 detection techniques.

2. The ASGARD facility and RISCS experiments

The ASGARD facility is a purpose-built site (location, N52°, 49'60□; W01°,14□60□) for the study of ecosystem responses to elevated soil CO_2 concentrations [CO_2]. CO_2 gas is delivered to as many as 16 field plots via 20 mm (ID) medium density polyethylene gas pipes. The pipes are sealed at the end but perforated over the final 21 cm and are inserted into the ground at an angle of 45º to the vertical so that the gas is delivered into the soil 50 - 60 cm below the centre of each gassed plot. Food-grade, liquid CO_2 is stored in two 200 L cryogenic vessels (BOC, Derby, UK) that are refilled as required from a road tanker. The liquid CO_2 is converted to gaseous form and down-regulated to ~152 kPa for delivery via a single inlet mass flow sensor (Alicat, Tucson, USA) to 16 individual mass flow controllers (Alicat) that regulate the gas flow to individual experimental plots. The mass flow controllers are operated, and the system data logged, by a PC-based control system (TVC, Great Yarmouth, UK).

Fig. 1 shows a general view of part of the ASGARD site. The experimental area was divided by crop type into three blocks of eight replicate 2.5 × 2.5 m plots with additional plots used as test areas. In each block, four randomly selected plots were treated with injected CO_2 gas and four acted as untreated controls. In the experiments described here, CO_2 was supplied to each plot at a constant rate of 1 L min^{-1}. The single point injection scheme generates a distribution of CO_2 in the soil ranging from high concentrations, sometimes above 50%, in the plot centre down to values approaching control levels at the plot edges. This distribution was used to investigate vegetation responses to soil CO_2. For analysis, sampling areas within the plots were zoned into low, medium and high CO_2, corresponding respectively to seasonal average soil concentrations of approximately 2-5%, 5-15% and >15%, as measured across the grid shown in Fig. 2 using a bar-holer and a Geotech GA2000 gas analyser (Leamington Spa, UK).

Fig. 1 The ASGARD site in 2006, showing pasture plots, CO_2 injection tubes (yellow) and gas measurement tubes (black).

2.1. Plant studies

Studies were carried out on a range of crop types to determine the sensitivity of plant types to elevated soil CO_2. Two experimental areas were used during the RISCS project. Pre-existing plots were used in 2010; new blocks of plots were established for RISCS and used in 2011 and 2012. Soil microbiology and detailed soil gas and flux measurements were carried out on a separate block in the old pasture plot area.

A grass/clover mixture was sown in eight plots to determine competition effects caused by differential stress effects on the two plant species. Following plant establishment, CO_2 gas was delivered to four plots from 21st March 2011 to 15th June 2012. Biomass was collected at about six-weekly intervals throughout the growing season by scissor cutting samples within a 20 × 20 cm square across two transects (7 samples) within each gassed plot and across one transect in each control plot (4 samples). Each sample was separated into the two species which were then weighed and dried. The plots were mown immediately following each sampling.

In the remaining plots two different crops were sown in each year: spring-sown barley and oilseed rape in 2010; beetroot and spring wheat in 2011. Seeds were sown in April and allowed to germinate and become established before gas was delivered. Crops were harvested when ripe, or earlier if weather or animal damage dictated. Biomass samples; stem height, dry weight and taken from each crop at harvest.

Root effects were studied by using a minirhyzotron (Bartz, Carpinteria CA, USA) a tube and camera system to count the number and length of roots in oilseed rape, grass/clover and wheat. Two minirhyzotrons were installed at a 45° angle to the vertical in each gassed plot and one in each control plot. They were positioned such that the tube at the South side of the plot passes through a low gas zone and the tube at the East side passes through a high gas zone. The Bartz camera is lowered down the tubes and an image is captured every cm down to a depth of approximately 60 cm. The root images were analysed using Rootracker software supplied by Bartz. Fig. 2 illustrates a plot layout with the measurement locations and infrastructure installed.

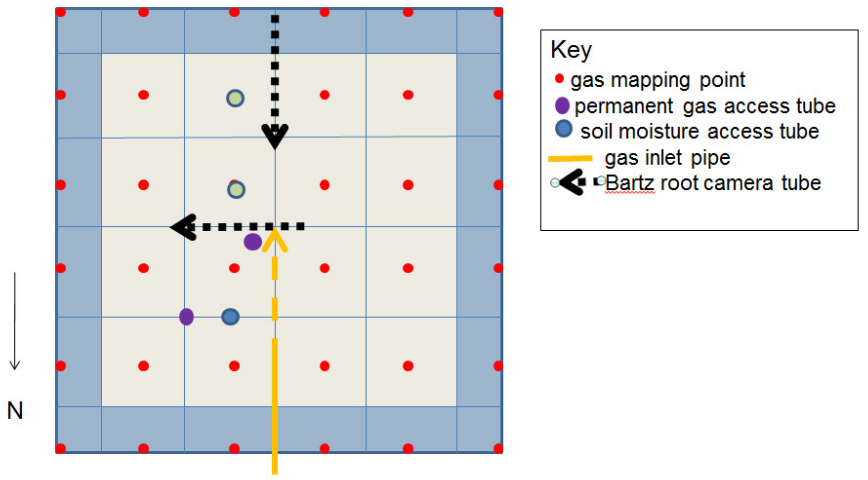

Fig. 2. Plot plan showing measurement locations and plot infrastructure. Samples for microbiological studies were taken in the centre of the squares marked by red circles. The shaded outer zone is a buffer; plant measurements were made in the central 16 squares.

2.2. Soil CO_2 concentration and flux measurements

Routine measurements of soil [CO_2] in each plot were carried out using a GA2000 landfill gas analyser (Geotech, Leamington Spa, UK) attached to the permanently installed gas access tubes (Fig. 1). In addition a continuous flux monitoring station consisting of a Licor LI-8100 system with four accumulation chambers controlled by an automated operating and data logging system was installed across two plots, one gassed, one control. The monitoring chambers were located as shown in figure 3. Within each sampling chamber, CO_2 flux, average [CO_2] over the 2-minute sampling period, humidity, atmospheric pressure and ground-level air temperature were measured, with data collected initially at 5-hour intervals for the first phase (3 - 17 August 2010), then at one-hour intervals for the second phase (17 August - 1 September 2010). An additional monitoring station (designed and constructed by the University of Rome) which continuously measured the concentration of CO_2 and CH_4, temperature, and atmospheric pressure at three separate points using remote probes was deployed to monitor the temporal variability of CO_2 on the ground surface and in the shallow soil of gassed and non-gassed plots, to determine CO_2 concentration ranges and exposure times for use in site modelling and biological studies, and to compare with other environmental parameters to better understand gas migration and accumulation processes. Probes 0 and 2 were buried underground to monitor gas concentrations in the unsaturated zone, with probe 2 placed near the centre of a gassed plot and probe 0 placed near the centre of an adjacent, non-gassed plot (fig. 3). Probe 1 was placed on the ground surface near the centre of the gassed plot, above probe 2, to monitor atmospheric concentrations at the soil-air boundary.

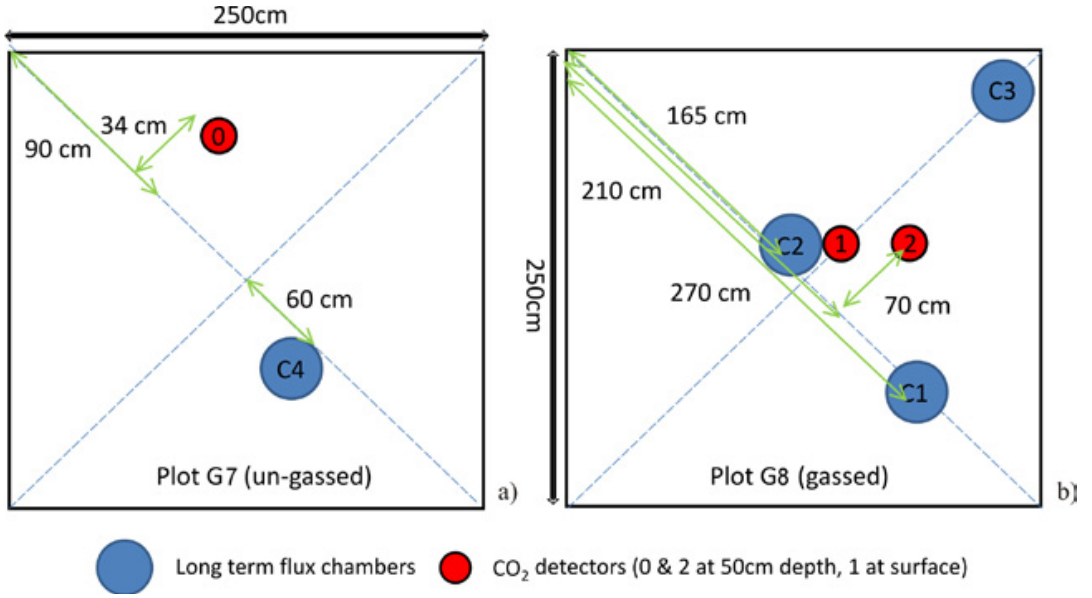

Fig. 3. Schematic map showing the spatial distribution of the deployed gas concentration and flux units, with the un-gassed plot on the left and the gassed plot on the right. The map is orientated with North at the bottom edge. The larger blue circles refer to the flux chambers and the smaller red ones to the probes. Probes 0 and 2 are at 50 cm depth while probe 1 is on the ground surface.

2.3. Microbiological studies

Studies in the pasture plots determined the effects of elevated levels of CO_2 on soil microbiology. Samples were taken from the centre of the 0.5 m squares (outlined with red dots on figure 2) using a hand held "Dutch" auger at depths of 15 - 30 cm, 45 - 50 cm and 65 - 70 cm. Epifluorescence microscopy was used to determine total cell counts and Adenosine Triphosphate (ATP) assay used for evaluating microbial activity [2]. To study the influence of induced CO_2 on important microbial metabolic pathways the aerobic methane oxidation and anaerobic methane and CO_2 production were determined both with and without oxygen by incubating soil samples at 20°C in 15 ml glass bottles with 3 g soil and in 119 ml glass bottles with 10 g soil. The glass tubes were sealed with butyl-rubber stoppers and screw caps/aluminium crimp caps, flushed with oxygen in case of the aerobic methane oxidation and nitrogen in case of the anaerobic methane and CO_2 production [3][4][5]. For inhibition of acetate dependent methanogenesis, 1% methyl fluoride (CH_3F) was added. For investigation of aerobic methane oxidation, 1% methane was supplemented. Headspace samples were analysed for methane and CO_2 by GC-FID (SRI 8610C, SRI Instruments, USA) gas chromatography equipped with a methanizer [6].

3. Results

3.1. Plant studies

Symptoms of plant stress are seen rapidly with visual changes to the vegetation observed within seven days of delivering CO_2 gas to the plots. Barley, wheat and grass leaves turned yellow and spring-sown oil seed rape and beetroot leaves turned purple within 7 - 10 days. Biomass changes were seen in all plants but to different extents. In grass/clover the mean total biomass collected over the season shows that in high gas zones the biomass of both grass and clover decreased, but whereas the clover biomass decreased by 79%, the grass decreased by 42%. Clover biomass was greater than that of grass in the control, low and medium CO_2 zones (fig. 4).

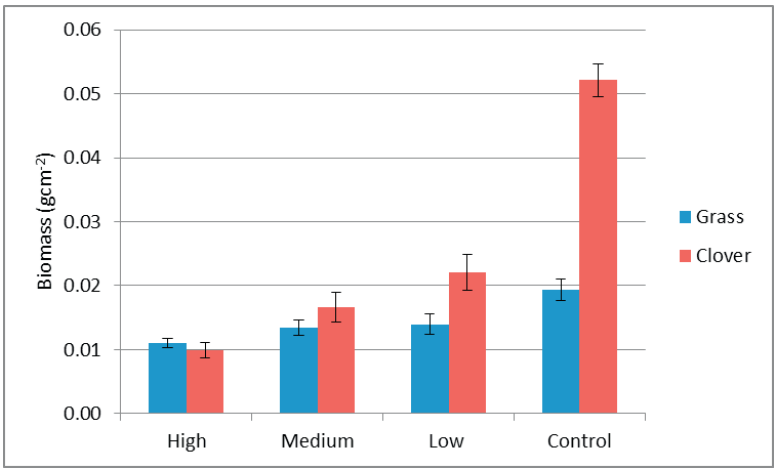

Fig. 4. Change in biomass (g cm^{-2}) of grass and clover growing in soil with high, medium and low concentrations of CO_2, collected between March and October 2011.

Rye grass, a monocotyledon, showed greater tolerance to high soil [CO_2] than clover, a dicotyledon. Similar results were found by Al-Traboulsi [7] who found that maize (monocotyledon) was more tolerant than field bean (dicotyledon). Decreases in biomass were also seen in spring sown barley and oilseed rape. In both plants the crop was shorter in the area of highest soil [CO_2]: oilseed rape was 30 cm shorter, barley was 10 - 20 cm shorter, than in the controls. In both barley and oilseed rape there was a 20% reduction in biomass but whereas barley grain number was reduced by 30% there was no significant reduction in the number of oilseed rape pods. Beetroot showed no significant difference in beet number, biomass or size but leaf biomass was reduced by up to 25% in areas of high [CO_2]. It is possible that the beet storage organs acted as a buffer so that decreased leaf biomass was not reflected in tuber size. Also, the roots of beetroot are very shallow and so may not have been affected by the higher [CO_2] at depth. These results show that high soil [CO_2] affects crops in different ways as in this instance the monocotyledon was affected more than the dicotyledon.

The root imagery shows that in oilseed rape the total number of roots in the control plots increased with time with most roots being present in the 10-19cm depth range (fig. 5). The number of roots counted before CO_2 injection commenced in the gassed plots was similar to the control plots. In the minirhyzotron at the south of the plot, the surface roots are subject to lower [CO_2] and here the number of roots in the 10 - 19 cm range were similar to the control plots, but towards deeper levels the roots are subject to higher [CO_2] and there were fewer roots as depth increased, with very few roots below 60 cm. The number of secondary roots at depth also decreased. In the minirhyzotron at the East of the plot which passes through the highest levels of soil [CO_2], there was an increase in the number of roots in the 10-29 cm range when compared to the control plots, but a decrease in the number of roots at greater depths. There were fewer secondary roots at all depth ranges.

In the grass/clover plots, it was not possible to differentiate the two species in the root images but the mean number of roots in the high gas zone (East tube) was generally greater than in the control (fig. 5). At depth there were fewer roots in the high gas zones. The results suggest that in some instances, the effect of soil CO_2 may be to stimulate the generation of roots.

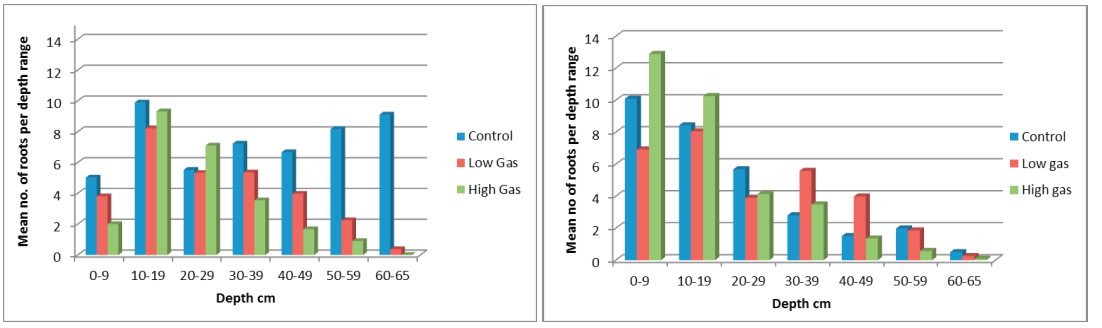

Fig. 5. Mean number of roots per depth range for oilseed rape (left) after 26 days gassing and grass/clover (right) after 67 days gassing.

3.2. Soil CO_2 concentration and flux measurements

Seasonal average [CO_2] in the permanent access tubes located 15 cm from the plot centre was 57% (±2% SE) and 44% (± 2% SE) in oilseed rape and barley plots respectively. In the tubes located 70 cm

from the centre, the corresponding values were 16% (±1%) and 4% (±0.4%). Control plot concentrations were 0.7 % (±0.02%, maximum 1.8%) and 0.8 % (±0.03%, maximum 3.4%) respectively.

Continuous monitoring of CO_2 concentrations in the shallow soil and on the ground surface using the three deployed probes has highlighted the variability of gas migration and accumulation as a function of meteorological parameters, gas supply, and unsaturated zone permeability. Data from the two buried probes showed a lateral interconnection between the gassed and non-gassed plots, with start-up and shut-down of gas injection flow resulting in clear responses in both probes that were typically offset by about 6 - 8 hours. Heavy rainfall events were seen to cause accumulation of CO_2 in the probe buried above the injection point, whereas low atmospheric pressure appeared to induce reduced [CO_2] in both buried probe locations possibly due to an increased flux out of the soil. Winter data appear to show accumulation due to a soil freezing event, with a rapid release to the atmosphere in the subsequent thaw. At the probe placed on the ground surface, a strong negative correlation was seen with wind speed, such that low wind conditions allowed accumulation of the denser-than-air CO_2 within the plant canopy while even light winds resulted in rapid and efficient mixing. This is illustrated in

Fig. , where these two parameters are plotted over a 2 week period. The diurnal nature of the wind patterns are clearly visible, with low wind during the night and higher winds during the day due to ground heating. As a result, higher CO_2 concentrations occurred at night (i.e. when photosynthesis is not occurring); this relationship can be quite sensitive, as wind speed minima near 4 knots in the first half of the period resulted in concentrations on the order of 0.7%, whereas winds closer to 1 knot (for longer periods) in the latter half yielded CO_2 concentrations as high as 2%. This diurnal cycling was most evident during the more meteorologically stable summer period, as major weather systems during the winter tended to make the winds stronger and more variable. Results from both buried and surface probes illustrate the variability of CO_2 concentrations even with a constant injection rate, and thus these results (concentration ranges, length of time at a given concentration, time of day for a given concentration) must be taken into account for accurate modelling of the impact of CO_2 leakage on physiological processes.

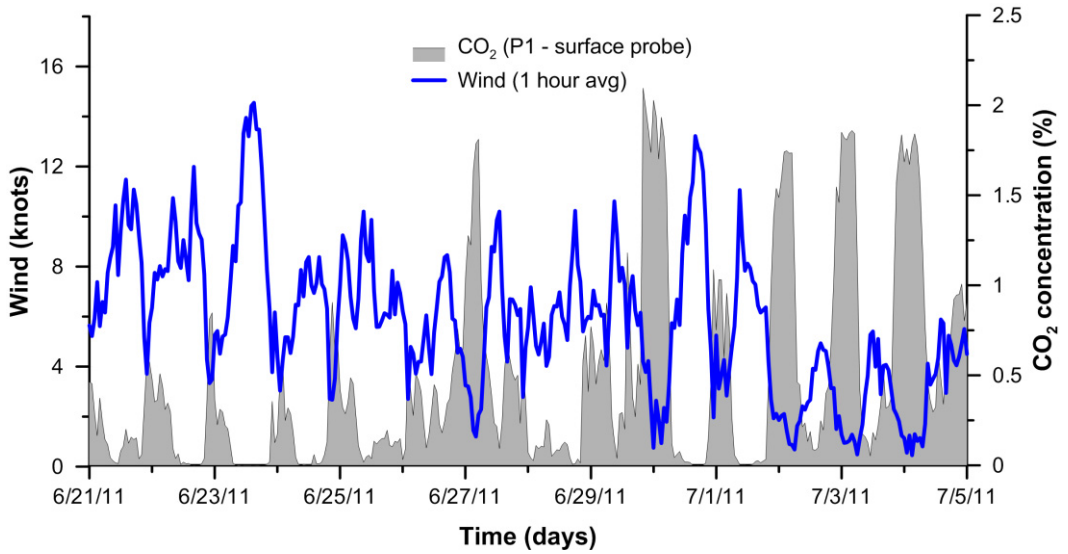

Fig. 6. Negative relationship between wind speed and CO_2 concentration on the ground surface

3.3. Microbiological studies

Previous work in the pasture plots has shown that in ungassed plots bacterial numbers fluctuate between 10^5 and 10^6 bacteria g^{-1} (wet weight) at the 15 – 30 cm depth sample, and that populations declined with depth by about one order of magnitude [2]. This was also reflected in ATP concentration. However, the bacterial numbers in 2010 did not decline with depth and varied between 5×10^5 and 1.5×10^6 bacteria g^{-1} at all depths. However, ATP concentration did decline showing that, although bacteria were present, they were relatively inactive. In 2006, bacterial numbers in the same gassed pasture plot declined from 1.9×10^6 to 2×10^4 bacteria g^{-1} during the three month period of gassing. This same observation was also made in 2010 when the numbers of bacteria in the gassed pasture plots also declined by one order of magnitude during the gassing period, suggesting that gassing soil with CO_2 impacts on microbial populations. By April 2011 numbers had declined to $\sim5\times10^5$ bacteria g^{-1} near the centre of the gassed plot where CO_2 soil concentrations were above 30%.ATP concentrations for both gassed and ungassed plots were also very low at this depth. In October 2011, ATP concentrations again varied with a decline of one order of magnitude between control and gassed plots (where soil [CO_2] reached as high as 79%).

Increasing rates of methanogenesis and decreasing rates of methane oxidation at high CO2 concentrations were demonstrated in the gassed plots. CO_2 production rates, which are an important indicator for microbial activity, showed decreasing trends under elevated CO_2 concentrations. Analysis of the microbial community composition by quantitative real time polymerase chain reaction showed alterations in microbial abundances under CO_2 influence with decreasing bacterial and archaeal DNA copy numbers. Variations in the microbial activity as well as in the microbial community composition depending on CO_2 concentration, seasonal variations and depth layers were observed.

4. Conclusions

Studies at the ASGARD facility have shown that elevated concentrations of soil CO_2 have a clear damaging effect on both the soil microbiology and vegetation growing in soil contaminated with high CO_2 concentrations. The extent of the effect depends on the concentration of the CO_2 and the type of vegetation and can affect competition between species in mixed canopies. It had been thought that dicotyledons were more susceptible than monocotyledons but studies at ASGARD have shown that this is not always the case. Continuous monitoring of CO_2 concentrations in the shallow soil and on the ground surface using *in-situ* probes has highlighted the variability of gas migration and accumulation as a function of meteorological parameters, gas supply, and unsaturated zone permeability.

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