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In Salah Gas CO_2 Storage JIP: Surface gas and biological monitoring

D G Jones[a] 1*, T R Lister[a], D J Smith[a], J M West[a], P Coombs[a], A Gadalia[b], M Brach[b], A Annunziatellis[c], S Lombardi[c]

[a]British Geological Survey, Kingsley Dunham Centre, Keyworth, Nottingham, NG12 5GG, UK
[b]Bureau de Recherche Geologique et Miniere, 3 Avenue Claude Guillemin, BP 36009, 45060 Orléans Cedex 2 – France
[c]Sapienza Universita di Roma, Dip. Scienze della Terra, P.le A. Moro 5, 00185 – Roma, Italy

Abstract

Surface gas and biological monitoring were carried out in 2009 at the In Salah Gas project (Krechba, Algeria), where geological storage of CO_2 has been underway since mid-2004. The CO_2 is removed from produced natural gas and re-injected below the gas-water contact on the flanks of the reservoir. The biological work was the first such study undertaken at the site. Observations were made in: uplifted areas around the three CO_2 injection wells, around the KB-5 well where breakthrough of CO_2 from the KB-502 injector had occurred, around the KB-4 well and in a background area away from CO_2 injection and gas production. Near ground atmospheric measurements were made with a mobile open path laser system, with soil gas and flux measurements in support of these and of a botanical and microbiological survey. Longer term monitoring was initiated for radon and other gases using buried probes and activated charcoal integrative collectors. Laser measurements appeared to show only natural variations, but interference from the vehicle exhaust, windblown dust and rain was apparent. Modifications are needed to overcome these problems. Natural variation of atmospheric CO_2 needs to be better constrained to identify anomalous values. Soil gas concentrations and fluxes were very low but slightly higher values over the KB-5 well could indicate low-level leakage. This is likely to be a legacy of breakthrough prior to the abandonment of the well. A variety of monocotyledonous and dicotyledenous plants was present, particularly in dry wadis or shallow depressions. The xerophytic flora and the microbial numbers were typical of such desert environments and the data provide baseline values since there were no indications of elevated CO_2. There were analytical problems with the microbial activity determinations but it can be concluded that activities were low.

Keywords: In Salah; CO_2; gas monitoring; biological monitoring; Algeria

1. Introduction

The In Salah Gas Project is a joint venture between Sonatrach, BP and Statoil. At the Krechba site, CO_2 stripped from natural gas is injected at a rate of 0.5–1 Mt per annum. Injection has been carried out since mid-2004 with almost 3 Mt emplaced to date [1]. The CO_2 is injected into a 20 m thick sandstone reservoir at approximately

* Corresponding author. Tel.: +44-115-936-3576; fax: +44-115-936-3446.
E-mail address: dgj@bgs.ac.uk.

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1800 m depth. The reservoir is an anticlinal structure with injection down dip of the natural gas reserves and the production wells. It is sealed by a 950 m thick succession of Carboniferous mudstones,which is overlain by about 900 m of Cretaceous sandstone and mudstones. Cretaceous carbonates outcrop at surface. Injection is through three deviated wells KB501, KB502 and KB503 (Figure 1). Satellite imaging (InSAR) indicates ground deformation has taken place around the injection wells [2-4] as a result of pressure-induced poro-elastic expansion of the storage reservoir in the area surrounding the injection points [5].

CO_2 injection at the In Salah site is on-going and a range of monitoring technologies has been or is being deployed. Other techniques are under consideration or have been considered and rejected [1]. The present study outlines the second deployment of near surface gas monitoring methods at the site, following an initial appraisal in August 2004 [6], and the first use of biological monitoring methods.

The storage of CO_2 in underground geological formations poses a very small risk of leakage to the surface. Monitoring strategies need to include a range of techniques to cover different monitoring requirements. Monitoring of the surface of a storage site is one method for the detection and mitigation of any leakage. The nature of CO_2 storage poses some challenges to surface monitoring:

1. The site must be monitored over its full life cycle, throughout the injection phase and after closure and well abandonment. The slow dissolution and reaction of CO_2 to form stable aqueous or mineral phases means that buoyant and mobile CO_2 can exist in the subsurface for tens to hundreds of years after injection has ceased [7]. Monitoring strategies need to be designed to cover this long time scale.

2. The mobility and migration of supercritical CO_2 (the preferred storage phase) and the large masses being injected in full scale storage projects mean that leakage could occur in a wide area (i.e. the risk footprint of the site may be greater than the actual area of the storage reservoir). Therefore, monitoring may need to cover large areas of ground at the surface.

3. Carbon dioxide is relatively abundant in the atmosphere (~380 ppm), groundwater, and soil, and detection of small leaks above background is problematic, particularly since the background itself is variable.

When considering the challenges above, surface monitoring surveys need to be deployed over wide areas, and be carried out relatively quickly and cheaply. However, they need to be sensitive enough to detect leakage, which may occur at different rates giving rise to variable near surface gas concentrations and fluxes. It is crucial to assess baseline conditions and their variability so that changes can be identified and quantified.

Surface gas measurements at Krechba were made in March 2009 by BGS with BRGM and Sapienza Università di Roma. The objectives of the short field visit were:

- To make near ground atmospheric measurements of CO_2 using a mobile open path laser system
- To obtain supporting observations of CO_2 and other gases in the very shallow subsurface (<1 m) by field and laboratory measurements and to obtain CO_2 flux data from the ground into the atmosphere
- To deploy buried probes for continuous monitoring of Rn and passive samplers (activated charcoal) for integrated monitoring to look at longer term gas migration effects.
- To make shallow groundwater measurements in existing water wells

The particular area of interest was between KB-502 and KB-5 (Figure 1) owing to the breakthrough of CO_2 from KB-502 into the latter well [1]. A secondary target was around KB-4. A background site to the west of the gas reservoir was also measured to provide contrasting data in an area well away from the producing zone and the CO_2 injectors.

Two Barasol probes were buried in excavated pits, one to the east of KB-502, close to the planned KB-602 aquifer monitoring well and KB-601 microseismic well, the second far away from CO_2 injection to the south near KB-7 (Figure 1). Passive sensors were deployed close to the three injection wells, KB-501-503, that near KB-502 being placed at the Barasol probe location (Figure 1).

Weather conditions were mixed, with fine weather being followed by unsettled conditions with appreciable amounts of rain. There had also been rainfall in the preceding weeks and significant amounts of surface vegetation were apparent, particularly in the wadis.

A second visit was made by BGS in November–December 2009. This was primarily to undertake biological baseline measurements for which supporting soil gas and flux measurements were made [8] The aims were to conduct a botanical survey and to assess microbial numbers and activity. The biological work centred on the three injection wells. A traverse was made from KB-5 south-eastwards towards KB-502, observations were made around KB-503, and on a traverse westwards from that well, and a traverse was undertaken north-eastwards from KB-501

(Figure 1). The opportunity was also taken to make further atmospheric CO_2 measurements in the areas of the injectors and measurements at the background site.

2. Methods

Gas Measurements

A Boreal Laser open-path laser CO_2 detector (2 µm wavelength with a sensitivity for CO_2 of around 5-10 ppm), mounted on the front of a Toyota Landcruiser 105, was linked to a GasFinder FC analyser. Data were collected every second with positions from either a Trimble ProXT or a Pharos GPS receiver. This system allows the rapid coverage of relatively large areas. The laser probe was mounted at a height of 38 cm (above flat ground), which was as low as could be achieved whilst maintaining safe ground clearance.

The probe used to collect soil gas samples consisted of an 8 mm diameter (4 mm ID), stainless-steel tube onto which two solid steel cylinders were welded to act as pounding surfaces when installing and removing the probe with a co-axial hammer. Prior to insertion, a sacrificial tip was fitted to the bottom of the probe in order to prevent blockage. Because of the hardness of much of the ground, most sites sampled in March 2009 were predrilled using a portable hammer drill before the probe was inserted. This does lead to potential problems with the effective sampling depth as a perfect seal between the probe and the predrilled hole cannot be guaranteed and gas may, therefore, come from around the probe annulus. All sites on the later visit were sampled by hammering in the probe.

In-situ soil gas measurements were mostly made with a Draeger X-am 7000, although some used a Geotechnical Instruments GA2000 or an LFG. All these instruments use an infrared analyser for CO_2 and CH_4 and electrochemical detection for O_2, H_2S (X-am 7000 and GA2000) and CO (GA2000). Soil gas was drawn to the instruments using their in-built pumps until a stable CO_2 reading was seen. The analyser was purged with atmospheric air between readings. The Draeger is limited to a 0-5% CO_2 concentration range, compared with 0-100% for the GA2000 and LFG20 and therefore should give better precision and accuracy at the low levels encountered.

In order to collect samples for laboratory analysis, at a number of sites a septum holder was attached to the upper end of the probe tube. The needle of a 60ml plastic syringe was inserted through the septum and gas was drawn up through the syringe and discarded to purge the probe. A 60 ml gas sample was then drawn up and injected into a previously evacuated stainless steel container. These containers were then transported back to the laboratory and analysed for hydrocarbon species (C1-C3 alkanes and C_2H_4) and permanent gases (N_2, O_2 and CO_2) using two Fisons 8000-series bench gas chromatographs. The resolution of the gas chromatographs is 0.1 ppm with an accuracy of ±5%.

CO_2 flux measurements were taken using a West Systems portable flux meter with a LICOR LI-820 IR detector connected via Bluetooth to an Acer n300 palm-top computer (PDA) with built in GPS positioning.

Barasol probes measure Rn gas concentrations continuously along with soil temperature and pressure The probes are autonomous and can operate for several months on their internal battery. Data is stored to built-in memory and downloaded when the instrument is retrieved. Radon can be carried by other gases and therefore may act as a natural tracer. It also provides indications of the fluctuations of gas e.g. diurnally, seasonally and in response to changing meteorological or ground conditions. The Barasol probes were buried vertically at a depth of 1 m in large excavated pits, which were then backfilled. Ground gas measurements were made in the base of each pit during Barasol deployment.

The passive samplers used comprise activated charcoal cloth, buried at a depth of 0.3 m in the same plastic pipe used for the Barasol or buried on their own in a similar way. They provide a cumulative record of the flux of gas and accompanying elements, which can be liberated from the sampler on return to the laboratory and analysed.

Biological studies

In order to cover the large areas needed for the surveys, widely spaced (100–200 m) sample points were used on each biological transect. Given the sparse vegetation in the desert setting, sampling points generally targeted vegetated areas in order to carry out a baseline botanical and microbiological survey. As such, the sampling points are not representative of the wider area, but hopefully reflect the flora present. A handheld GPS receiver was used to locate the sampling points.

At each sample location, a 0.5 x 0.5 m quadrat survey was taken on a 2.5 m cross from a central point (where the soil samples and gas measurements were normally taken). For each quadrat the percentage area covered by each plant was estimated and photographs and samples taken to aid species identification.

Soils were sampled with a Dutch auger, at 10–20 cm, 30–40 cm and, where possible, 40–50 cm depth. The auger head was cleaned with disinfectant wipes to minimise contamination. Sub-samples were taken for immediate analysis to evaluate microbial biomass by adenosine tri phosphate (ATP) assay using a Deltatox analyser and also preserved for determination of microbial numbers using epifluorescence microscopy in BGS laboratories. Further details of the methods can be found in Smith et al. 2010 [8].

3. Results

Gas Measurements

The mobile laser data were plotted using Jenks' Natural Breaks in ArcMap v9.2 to define the different classes. This identifies break points by picking the class breaks that best group similar values and maximise the differences between classes by iteratively comparing sums of the squared difference between observed values within each class and class means.

Traverses with the mobile laser were first made on the plateau around KB-502. They were then extended to the area between KB-502 and KB-5 to cover the area of uplift and look for any surface manifestation of the known migration of CO_2 between the two wells [1].

The majority of data values were close to a 'normal' atmospheric level of around 380 ppm CO_2 with the differences between classes being only small (a few tens of ppm). The highest values, and only marked changes in CO_2 concentration, to in excess of 500 ppm, were seen around the KB-502 well itself and were clearly related to the vehicle exhaust being blown forward into the laser probe (Figure 2). Thus, with the wind coming from the south to south west, higher values were seen on the NE side of the well on a clockwise circuit and on the west side on an anticlockwise circuit. Similar effects were seen elsewhere and could not always be avoided despite careful planning of the direction of survey lines.

Mobile laser measurements were made near KB-5 and then in the accessible parts of the wadi floor between KB-5 and KB-502. A number of circuits were made around the outer perimeter of the KB-5 well pad. At certain points rapid increases in CO_2 concentration were observed, but these were almost certainly from the vehicle exhaust. However, more subtle variations (several tens of ppm) were also seen and these appeared, from examination of the data in the field, to occur consistently in an area to the SE of the well on different circuits. Static measurements were therefore made at this location with the vehicle engine switched off (Figure 3). Initially there were slightly higher values (400–420 ppm) but they tailled off over time to 380–400 ppm. Soil gas and flux measurements were made at this location and around the rest of the well pad, but showed no signs of higher CO_2.

Similar apparently higher values were also observed over the area of uplift to the east of KB-5 but once again the values fell when observed over a longer time period. It seems likely that such fluctuations of 30–40 ppm are within the natural diurnal variation and this needs to be considered when trying to detect a leakage signal above background. Soil gas and flux measurements at this location gave low values (0.04 % CO_2 and negative flux).

Traverses with the open path laser around the KB-4 well showed changes that could be attributed to rainfall affecting the measurements both directly and through splash-up of dirt onto the laser optics. Other than differences seen during and after rainfall no obvious elevated atmospheric CO_2 values were seen. However, soil gas CO_2 readings, although low did appear to be somewhat higher than elsewhere ranging from 0.16–0.27 % for lab results and 0.06–0.19 % for the most sensitive field instrument. This contrasts with the majority of sites where most of the data were close to atmospheric levels (0.03–0.05 %).

A series of lines were run with the open path laser in a background area to the west of the gas field. These covered the same area where point measurements were made in 2004 [6]. Surface gas/flux measurements were repeated at similar locations to 2004. It also rained during these traverses, which had some impact on the laser results. The field soil gas and flux measurements were all very low at the background sites, with CO_2 concentrations at or only slightly higher than atmospheric levels and flux levels no higher than 5 g m^{-2} d^{-1}.

Some additional gas data were obtained during the November-December visit, although this was focussed primarily on biological observations and associated gas measurements. The atmospheric data obtained with the laser system were affected by the very dry, dusty and rather breezy conditions. Some vehicle exhaust effects were seen, but a more serious problem was the varying amounts of airborne dust both within the laser beam and settling on the external optical interfaces. It was hard to separate the effect of dust from real variations in atmospheric CO_2 content. Cleaning the probe windows had only a relatively minor effect, suggesting that dust in the air had more of an influence on the data. However, certain lines where windblown dust should have been less of a factor, owing to the strength and direction of the wind, suggest that higher CO_2 concentrations (in excess of 500 ppm) are possible in this kind of environment.

The only soil gas CO_2 values above 1.0 % were seen directly over the KB-5 well, in unconsolidated sand in a trench at the wellhead. It is most likely that they are a relict of breakthrough prior to the full abandonment of the well. Some slightly higher values (0.5–0.8 % CO_2) was also seen in the bottom of the 2 m deep pit dug for the Barasol probe to the SE of KB-502. These may indicate true gas concentrations, free from atmospheric dilution, as they are from holes drilled into bedrock rather than in highly permeable sand and gravel.

Data were only obtained from the Barasol radon probe near KB-502; the probe near KB-7, intended to measure background values was faulty. Results were obtained from 27/03/2009 until 01/03/2010. The raw data show a narrow pressure range (942 to 967 mBar) and wider temperature variation (12.1 to 31.3°C). The average Rn value was 1.45 $kBq.m^{-3}$ with small peaks in the range 6-14 $kBq.m^{-3}$. Preliminary analysis does not suggest CO_2 leakage.

The passive sampler (activated charcoal) leachates display slight contamination either by carbonate (Ca, Mg), clay and/ or sand (Si, Al). There were no indications of deep transport by CO_2 on an initial appraisal.

Biological studies

All the plants observed were typical desert flora, identified using Ozenda (2004) [9] and Sahara-Nature.com, and all were seed-formers (Spermatophyta). A variety of angiosperm (flowering plant) families were detected (e.g. Compositaceae, Graminaceae, Brassicaceae) with both monocotyledonous (e.g. Graminaceae) and dicotyledonous (e.g. Compositaceae) groupings present. One gymnosperm family was also observed (*Ephedra* spp). All exhibit typical xerophytic adaptations (reduced leaves, thick stems) necessary for life in an arid environment. The Krechba area was sparsely vegetated at the time of this visit, with large expanses of ground completely free from visible flora. In any given sampling area, vegetation cover (Figure 4) was never higher than 50%, and was commonly around 10%.

Vegetation was more plentiful in dry wadi channels, where there may be water at depth and in shallow depressions where water would collect temporarily, as seen on the transects between KB-5 and KB-502 and to the east of KB-503. The KB-501 transect, on the plateau, provided conditions more representative of background for the region. The dicotyledenous angiosperm (*Hammada* spp) dominated here with other unidentified plants .

The ATP results appear to have been affected by a contaminated blank giving rise to negative values. This implies the samples had a disinfecting quality and/or the change in pH caused by adding sample to the de-ionised water produced conditions outside the tolerance range of the microbial population.

In general, microbial counts averaged ~10^5 g^{-1} at 10–20 cm depth although ~10^6 g^{-1} were observed in two samples (Figure 4). However, some samples had so few organisms present that it was not possible to obtain meaningful results. At 30–40 cm depth numbers vary between ~10^4 g^{-1} to ~10^5 g^{-1} although fewer samples were taken because of sampling difficulties. Even fewer samples were taken from 40–50 cm but numbers remain at ~10^5 g^{-1} where counts were possible. Two samples had zero counts meaning that the samples from these sites were devoid of microbial life.

Soil gas concentrations on the transects at 90 cm depth were very low; most values were at or below atmospheric levels (Figure 4). The exceptions were 2 sites on the KB-5 to KB-502 line and 2 on the KB-503 transect, which reached 0.09 to 0.15% CO_2. Fluxes were also low, mostly less than 2 g m^{-1} d^{-1} (Figure 4). Higher values (5–9 g m^{-2} d^{-1}) were seen at a few points on the KB-5 to 502 and KB-503 transects.

4. Discussion

It is clear from experiences with the mobile open path laser system that the readings can be affected by vehicle exhaust gases, rain, dust in the atmosphere and dust or dirt on the windows of the laser probe.

The impact of exhaust gases can be minimised by running lines at right angles to the wind direction and moving upwind. However, the terrain, or the need to cover a particular feature (e.g. the area of uplift) may constrain the line direction. The only way to totally eliminate exhaust problems would be to use an electric vehicle, but this is not a viable option at Krechba. An alternative is to extend the tail pipe of the vehicle exhaust to increase the likelihood that the gases are mixed and dispersed away from the laser probe.

Dust in the atmosphere and on the windows of the laser probe can cause higher apparent readings. Alternatively, in wet conditions, the lenses can get muddy because of splash-up from the ground and this can cause reduced values and noisy data, which are only rectified by cleaning. A dust cover for the probe is being considered although this might reduce the response time.

Natural background atmospheric CO_2 concentrations vary during the day and this needs to be considered. Measurements of CO_2 fluxes have been made at different sites around the world, normally with eddy covariance techniques. However, although these studies involve measuring the CO_2 concentration and flux at high frequencies (e.g. 10 Hz) the data are more often reported in terms of net long term fluxes. The short term variability is not therefore readily obtainable from publications. Measurements are usually made at a height of 2 m or greater and so may not be indicative of values closer to the ground. Also it is more usual for the readings to be made in vegetated areas, such as grasslands or over forest canopies. There appear to be few data for desert areas with very sparse vegetation cover.

A better understanding of natural variability in near ground CO_2 values would help greatly in identifying gas anomalies. It could then be used to determine methods for identifying anomalies. The indications at present, from the data collected so far at Krechba, would suggest that atmospheric CO_2 varies on the timescale of a few minutes and longer. Thus a strategy to identify anomalies could involve looking for shorter term changes in CO_2 concentration (seconds to tens of seconds) and ignore longer term trends. This would, however, require the elimination of the other effects of vehicle exhaust, rain and dust.

Shallow soil gas and flux measurements are problematical at Krechba because of the hard ground, although it is possible, with patience, to get measurements in most places. The highly permeable dry gravel and sand adds a real risk of atmospheric gas being drawn down through the substrate into the analyser.

A solution to this problem would be increasing the depth of sampling. A network of shallow boreholes (5–10 m depth) was proposed after an initial visit to Krechba [6]. However, this approach is not readily amenable to the rapid investigation of an atmospheric CO_2 anomaly.

Soil gas and flux data from the two visits show clearly the higher CO_2 concentrations in March in one of the Barasol pits. These were taken in bedrock and thus less susceptible to atmospheric dilution. They may better reflect the true ground CO_2 concentrations. Laboratory data were somewhat higher and this may be because the sampling method (involving withdrawal of a much smaller volume of gas than the in situ measurements) minimised atmospheric dilution. Other field data show CO_2 concentrations at or below atmospheric levels except for sites near KB-4, measured under wet conditions that might have reduced atmospheric ingress. Fluxes in March were mostly below 5 g m^{-1} d^{-1}.

Data from the later visit show the anomalous nature of the CO_2 concentrations measured at the KB-5 wellhead, which are also reflected by some of the higher flux readings. These suggest that the KB-5 data merit further investigation as they could indicate leakage from the well. Other sites showed somewhat higher CO_2 concentrations and fluxes than seen in March (albeit still very low values) and these may reflect biological production as a bias towards vegetated areas was necessary for the botanical work.

In comparison with more vegetated sites from temperate regions the soil gas values are lower by at least an order of magnitude. The flux rates are also lower in general by an order of magnitude although the highest values (> 1 g m^{-1} d^{-1}) overlap with typical autumnal temperate flux rates. All the results from this study provide baseline data after more than 2 months without rain (TuTiempo.net, 2010).

The botanical study revealed a wide range of plants at Krechba, all of which exhibited xerophytic characteristics (e.g. reduced leaves, thick stems) necessary to survive in the arid conditions. All those observed were seed-formers (Spermatophyta). A variety of angiosperm (flowering plant) families were detected with both monocotyledonous and dicotyledonous groupings present. Sensitivities to exposure between monocotyledonous and dicotyledeonous plants to different CO_2 soil gas concentrations have been demonstrated in temperate climates [10, 11] so there is the potential for these same plant groupings to have similar sensitivities in this desert environment.

It is likely that, after rain, short-lived annuals would appear which would rapidly complete their cycle, producing seeds to survive through the drought until the next rain event [9]. Characterisation of these plant families and species would only be possible during and immediately after rain which often falls in March/April.

In general, microbial numbers observed are typical of desert aerobic microbial populations [12] where numbers vary from <10 (Atacama Desert) to 1.6 x 10^7 g^{-1} in soils of Nevada. Microbial activity in this environment is highly dependent on the availability of moisture but other factors, such as temperature and nutrient availability, will also play a role. It would be useful to carry out the same evaluation after a period of rain to ascertain the microbiological background under these conditions, whilst also observing the change in the flora.

This study did not establish the types of microbes present – only the numbers present. It is extremely likely further analysis of the composition of the population will reveal a complex ecosystem as suggested in other studies [e.g. 12–14]. A qualitative conclusion from the problematical ATP measurements was that the microbial ATP in Krechba samples is generally low (below the contaminated blank in all cases).

The data presented in this study represent a baseline survey of plant life, plant coverage and microbial activity in the soils of the Krechba site. Soil gas data do not indicate any CO_2 leakage except possibly at KB-5. However, the higher values there are not likely to reflect continuing leakage as the well has now been completely sealed and abandoned. This could be verified by further measurements. As expected for a hot, dry, low nutrient ecosystem, microbial populations and total vegetative cover were low. Plant life in particular exploits topographic lows, presumably to make better use of the little water available. In spite of the environmental factors and scarcity of vegetation, plant diversity is relatively high, with monocotyledonous and dicotyledonous angiosperms, and gymnosperms represented by a number of species.

Acknowledgements

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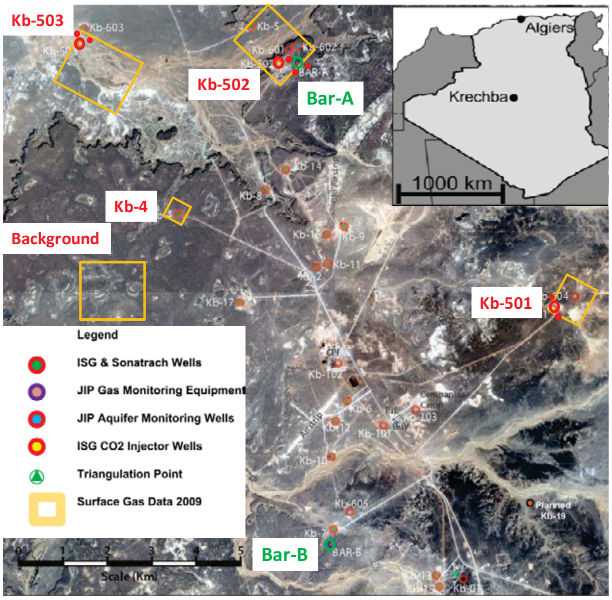

Figure 1. Location map of Krechba field on Quickbird satellite image with main study areas. Bar-A and Bar-B are Barasol locations. Solid red dots are passive sensor locations. Inset map shows location of Krechba in Algeria

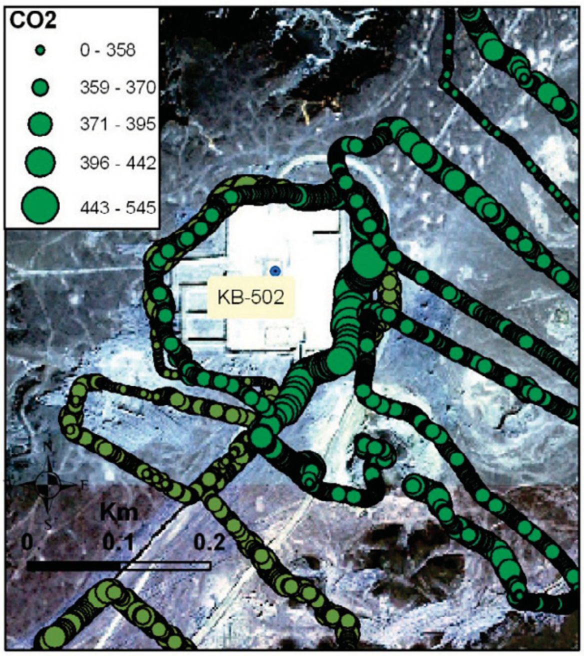

Figure 2. Data for near ground atmospheric CO_2 (concentrations in ppm) from mobile open path laser measurements around KB-502. Note higher values to the east and NW of the well due to vehicle exhaust affecting measurements with the laser probe

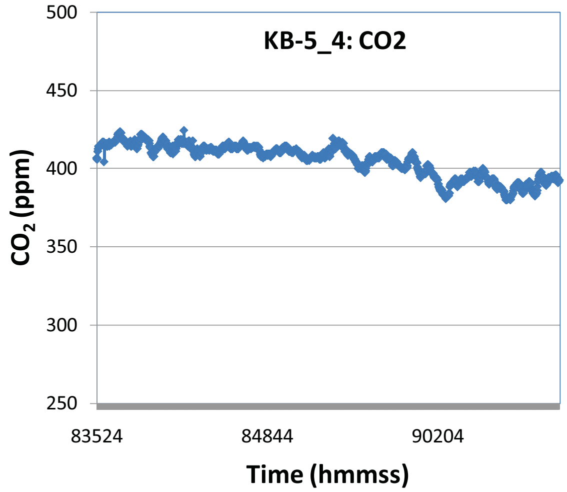

Figure 3. Static measurement of near ground atmospheric CO_2 SE of KB-5 in area of apparently higher CO_2. Note decline with time

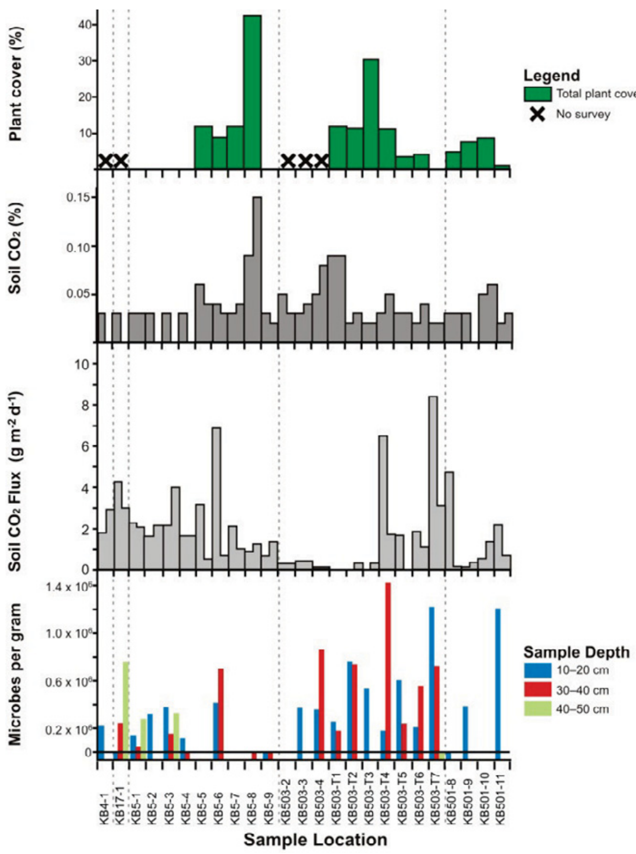

Figure 4. Comparison of microbial counts, soil CO_2 concentration and plant coverage datasets.