# OR/17/049 Soil gas

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Ward, R S[1], Smedley, P L[1], Allen, G[2], Baptie, B J[1], Daraktchieva, Z[3], Horleston, A[7], Jones, D G[1], Jordan, C J[1], Lewis, A[4], Lowry, D[5], Purvis, R M[4], and Rivett, M O[6]. 2014. Environmental baseline monitoring project: phase II - final report. *British Geological Survey Internal Report*, OR/17/049.
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## Introduction

The soil gas element of the project sought to establish baseline conditions for the concentrations of gases in the soil, flux of key gases from the soil to the atmosphere and near-ground atmospheric levels of gases. There is therefore some overlap with the atmospheric monitoring (Atmospheric composition). Since radon was measured at a subset of the surveyed locations there is also some linkage to the radon work (Radon).

Baseline soil gas measurements, like those for the other parts of the project, provide a basis against which to assess any future changes that might result from shale gas activities. Although of low probability, there is the potential for gas to escape from depth along geological pathways (faults, fractures and other higher permeability zones) or man-made features, especially wells (either pre-existing or drilled for shale gas exploration, evaluation or development).

Whilst large faults may be known from existing geological maps and/or data acquired during hydrocarbon exploration (e.g. 3D seismic data), or become apparent from seismicity or ground motion studies, smaller faults and fractures may be present but unknown. The completion (plugging and abandonment) of existing deep boreholes could be of variable quality depending on the age of the well; there are wells in the Vale of Pickering that are more than 50 years old. New wells also represent a potential pathway.

It is very difficult to predict where fluid migration from depth might reach the surface whether it follows natural or man-made pathways. Natural seepage of gas along faults tends to occur at limited sites, metres to tens of metres across, along only a very small proportion of the fault length (e.g. Annunziatellis et al., 2008[1]; Johnson et al., In press[2]; Ziogou et al., 2013[3]). Borehole leaks can occur at the wellhead or, if fluid escapes from the annulus of the well, can reach the surface up to several kilometres away (e.g. Allison, 2001[4]).

Although soil gas monitoring is not a statutory requirement for shale gas activities, it is necessary at landfill sites (Environment Agency, 2010[5]) and is often used to satisfy regulatory requirements for monitoring at geological $CO_2$ storage sites (European Union, 2009a[6], b[7]).

## Monitoring site (or data) selection and supporting information

The general principles of the approach were set out in the Site Selection report (Smedley etal., 2015[8]). The aim was to acquire a representative dataset that reflected the spatial and temporal

variability of baseline soil gas conditions in the Vale of Pickering in the vicinity of the proposed shale gas activity at KM8. This was carried out within the constraints of logistical requirements and budgetary limits. For example, landowner permissions are needed for access and continuous monitoring needs to be in secure locations, safeguarded against human or animal interventions, where mains power is an advantage.

This soil gas study included field measurement of methane, $CO_2$ (which could be produced from methane oxidation or present in reservoir gas), $O_2$ (useful in helping determine the source of $CH_4$ and $CO_2$) and Rn (a possible tracer of gas migration pathways). The trace gases $H_2S$ and $H_2$, were also included.

A mix of survey mode (single point and mobile) and continuous measurements at selected sites was carried out. Surveying large areas for discrete surface gas outlets is best conducted with mobile equipment to identify locations of specific interest. However, due to dilution in air, sensitivity is reduced. Single-point measurements provide the highest sensitivity as the gas is extracted from the soil or soil surface where concentrations are highest, and a sufficient number of analyses over a site provide a good indication of the range of baseline conditions. Continuous measurements at a small number of sites provide information on temporal variations (e.g. diurnal or seasonal changes).

It was the intention to supplement field measurements with a subset of duplicated laboratory determinations of soil gas concentrations. This would have provided information on additional gases, such as other light hydrocarbons, and verified field determinations with higher precision data. However, this would have significantly reduced the amount of field data, through diversion of effort and has therefore not yet been undertaken.

## Monitoring (or data processing) activities

The study included:

- detailed coverage of near-ground atmospheric methane and $CO_2$ using mobile open path lasers;
- broad-scale grids of point measurements of soil gas ($CO_2$, $CH_4$, $O_2$, $H_2$, $H_2S$ , Rn) and flux ($CH_4$ and $CO_2$) in the field;
- for specific sites, continuous measurement of atmospheric methane using a scanning open-path laser, $CO_2$ flux using accumulation chambers and eddy covariance techniques and continuous measurements of soil gas $CO_2$ concentrations using buried probes.

The soil gas surveys (mobile and point measurements) were carried out on two farms to the east of Kirby Misperton (Figure 111). They included areas of lacustrine and alluvial deposits (Ford et al., 2015[9]) on Ampthill Clay Formation and Kimmeridge Clay Formation (Undifferentiated) and also the inferred surface locations of a number of major E–W faults (Newell et al., 2015[10]). Boreholes on one farm (Farm A) had shown higher concentrations of $CH_4$ in groundwater.

Continuous soil gas monitoring was concentrated close to one of these shallow wells in the vicinity of one of the new groundwater wells drilled for the project, in order to link the soil gas and groundwater studies.

The other continuous monitoring was sited at KM8 (Figure 111) to supplement the atmospheric monitoring already in place there with automated accumulation chambers to measure local $CO_2$ flux and a scanning laser system to measure $CH_4$ across the KM8 well pad. In addition an eddy covariance system was installed at Preston New Road in Lancashire to provide $CO_2$ flux information

in conjunction with the atmospheric monitoring.

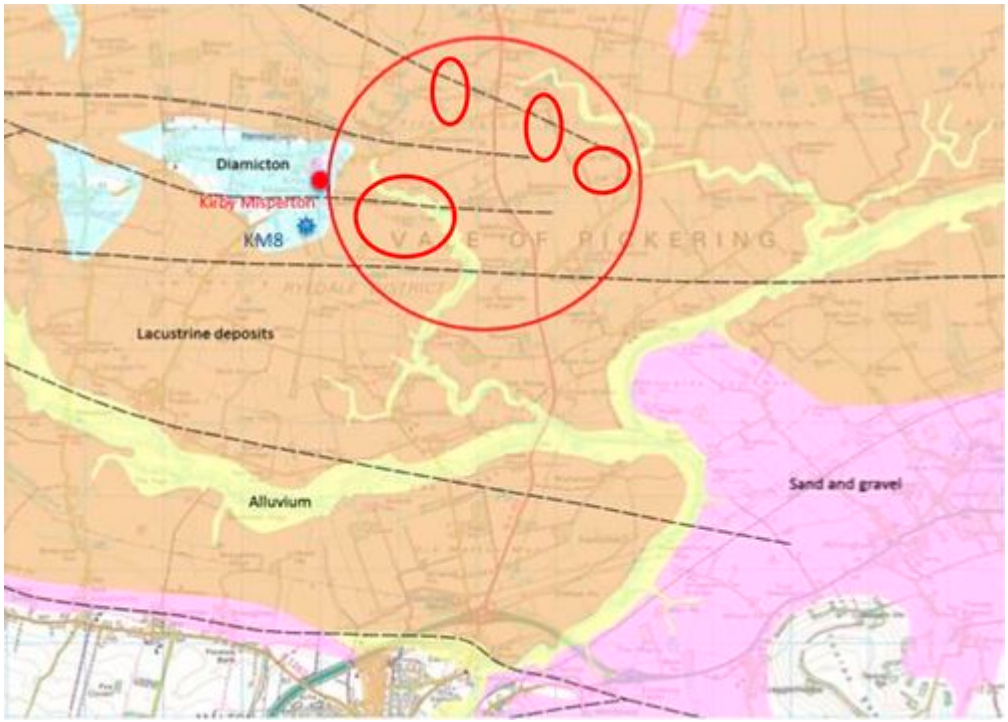



**Figure 111** Soil gas study area to the east of Kirby Misperton within the red circle. Includes mapping data licensed from Ordnance Survey. © Crown Copyright and/or database right 2017. Licence number 100021290 EUL.

# Results

## Spatial surveys

Three separate surveys were carried out in the Vale of Pickering in June, August and October 2016. These supplement the more limited work that was possible in November 2015 and March 2016 when ground conditions were relatively wet. In contrast the soil was generally dry in the spring to autumn of 2016 enabling soil gas data to be obtained at most sites.

Equipment availability and some instrument issues meant that full datasets were not possible with all techniques on every visit. On the other hand, additional instruments were available in 2016–17, which significantly improved the measurements possible, especially of $CH_4$ concentration and flux. The data obtained from all the baseline surveys is summarised in Table 17.

Table 17 Summary of survey soil gas data acquisition (X good coverage; x limited data).

| **Technique** | **Survey period** | | | | |
|---|---|---|---|---|---|
| | **November 2015** | **March 2016** | **June 2016** | **August 2016** | **October 2016** |
| Mobile $CH_4$ laser | | | X | X | |
| Mobile $CO_2$ laser | | | X | X | X |
| $CH_4$ in soil gas | | | X | | X |
| $CO_2$ etc. in soil gas | X | | X | X | X |
| Rn in soil gas | | | X | X | X |

| | | | | | |
|---|---|---|---|---|---|
| $CH_4$ flux | | X | X | X | X |
| $CO_2$ flux | X | X | X | X | X |

The results for $CO_2$ concentration and flux are summarised in Figure 112. They show general seasonal trends with higher fluxes due to enhanced biological activity in the spring and summer compared with the autumn and winter. This is best exemplified at Farm B. At Farm A the spring (June) values are somewhat higher than those for August, which probably reflects different crop growth and management practices. The higher $CO_2$ concentrations in November 2015 are almost certainly caused by the high soil moisture inhibiting the (relatively low) flux from the soil and creating a build-up of gas in the soil pores.

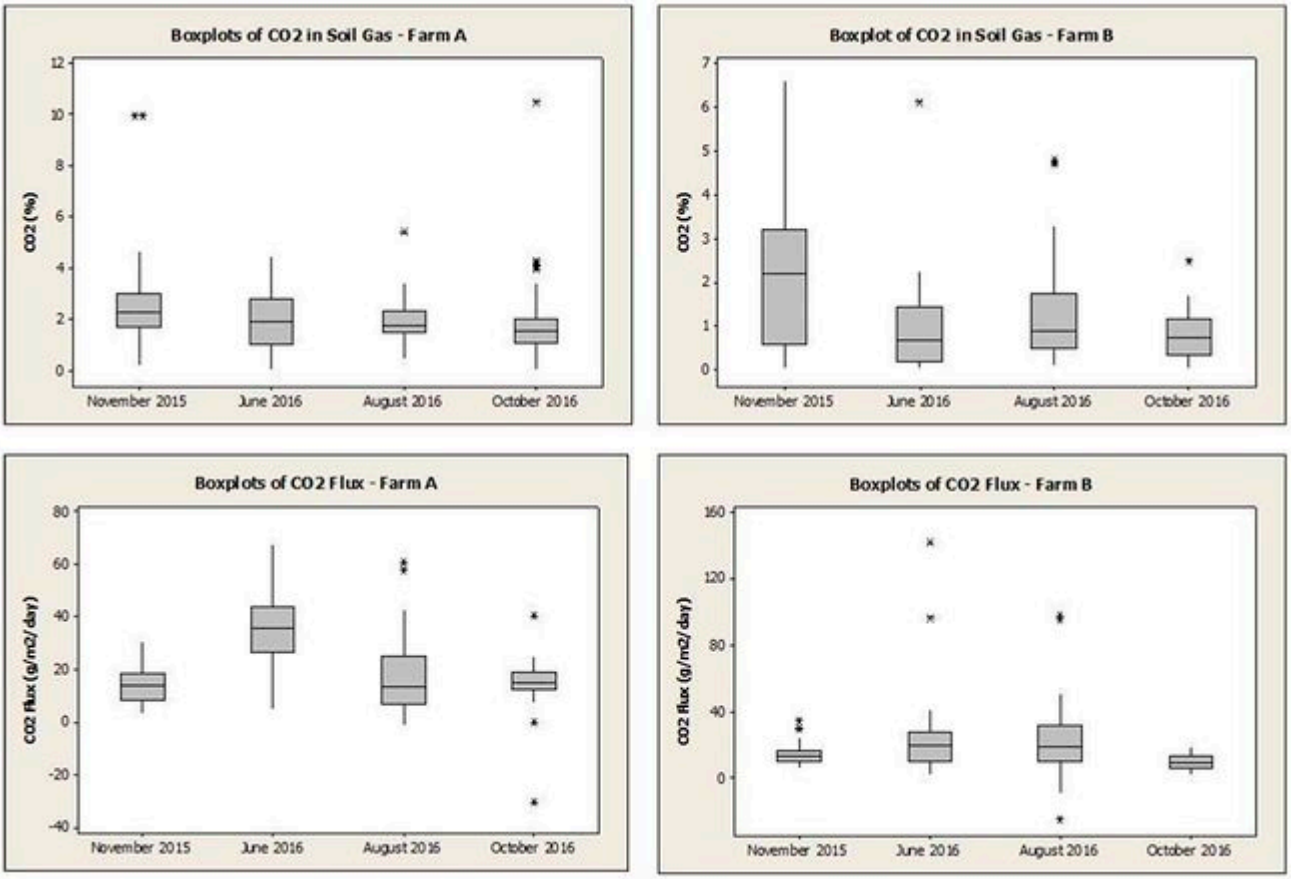



**Figure 112** Boxplots summarising all survey data for $CO_2$ concentrations and $CO_2$ flux at the two farm sites.

Methane in the soil shows a narrow range of concentration values (Figure 113), which was only slightly higher at each of the farms in June compared to October 2016. The upper limits of the data were constant at 3.3 ppm, less than double the baseline atmospheric composition of about 1.9 ppm and well within the range of atmospheric values measured at KM8. This suggests that very little methane is being produced in the soil in the areas sampled, or that any produced is being efficiently oxidised to $CO_2$. Methane fluxes were very low, mostly below the detection limit of the instrument (0.016 g $m^{-2}$ $d^{-1}$), and only exceeded this at two sites in June 2016 with a maximum of only 0.058 g $m^{-2}$ $d^{-1}$.

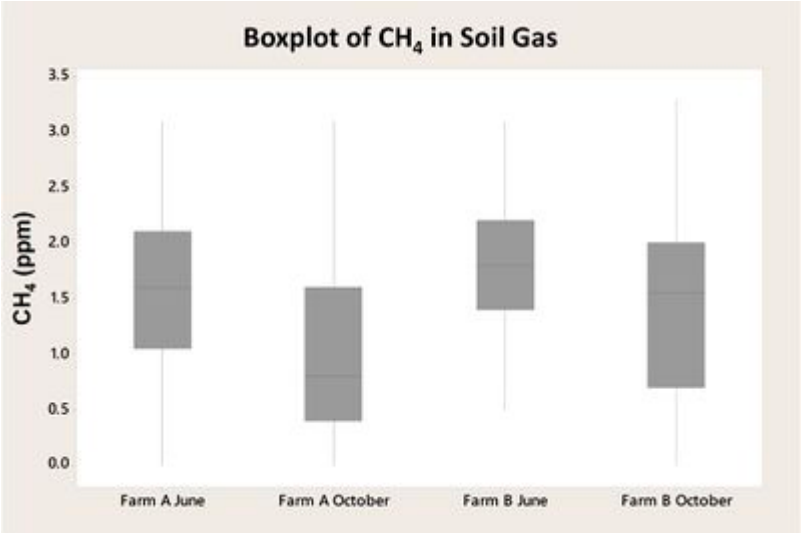
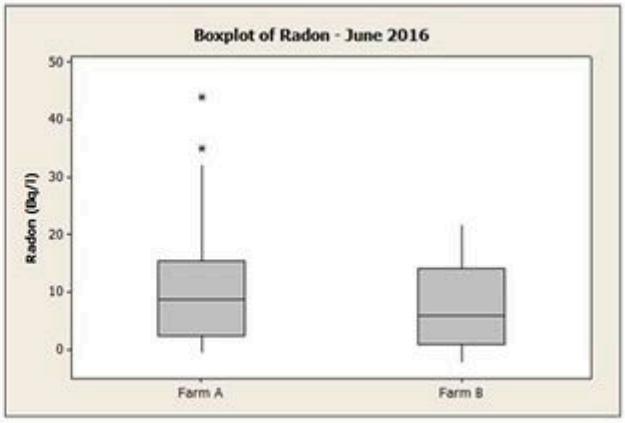
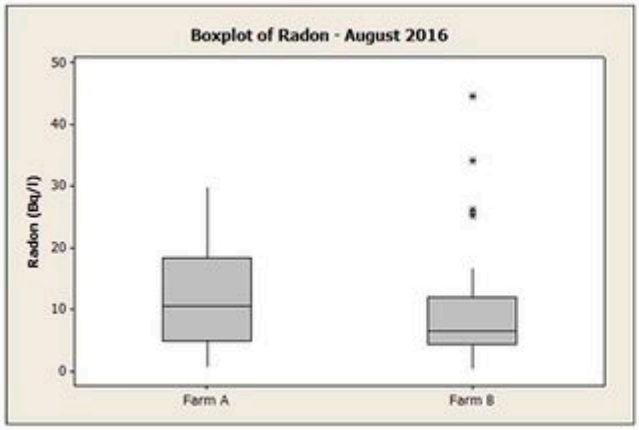



**Figure 113** Boxplot of $CH_4$ concentrations at the two farms sampled in June and October 2016.

Radon results (Figure 114) vary between the two farms, with most measurements at Farm B being somewhat lower than Farm A, probably because of variations in soil composition and permeability. The radon data showed similar overall ranges for all the surveys but differ in some details. The median values, and bulk of the measurements, at Farm A were slightly higher than Farm B, with quite similar statistical distributions in June and August 2016. A greater number of measurements in October 2016 were higher, with an appreciably higher median at Farm A. This suggests generally damper soil conditions causing the gas to build up. The lower $CO_2$ values for this survey, compared with the spring and summer visits, can be explained by lower biological production of this gas in the autumn and its greater solubility/reactivity in soil pore water. Differences between surveys will also reflect the varying number and locations of points sampled, as it was not possible to measure Rn at all sites because this is significantly more time consuming than the other measurements.



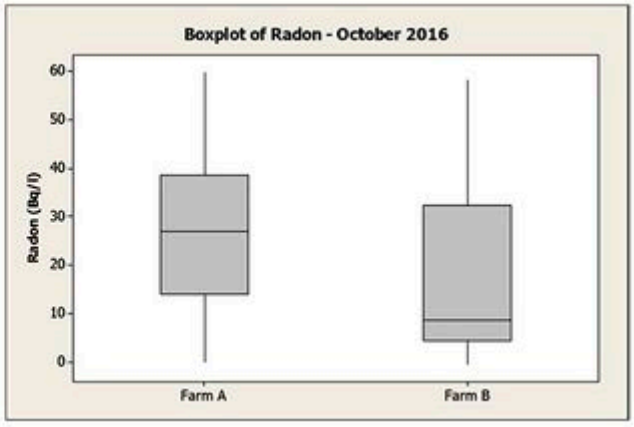



**Figure 114** Boxplots of Rn in soil gas for the 3 surveys in 2016.

Spatial variations in soil gas and flux are compared in Figure 115 to Figure 118. Whilst there are broad patterns of relatively higher and lower $CO_2$ concentrations in the different areas of measurement (Figure 115), individual points do not tend to match well between surveys. This is perhaps not surprising as the precise re-sampling of the same site was not possible and points could differ by a few metres between surveys. Thus the differences seen probably reflect small-scale variations of the soil in terms of Rn production and permeability. There appears to be little consistency in the spatial patterns of $CO_2$ flux (Figure 116) between visits, whereas some higher Rn values (Figure 118) appear to be fairly persistent. This is to be expected as Rn is produced from the radioactive decay of uranium and so, provided soil permeability is relatively constant during the drier period of the year, it should not be affected by seasonal variations in the same way as gases and fluxes ($CO_2$, $CH_4$) that are strongly linked to biological activity.

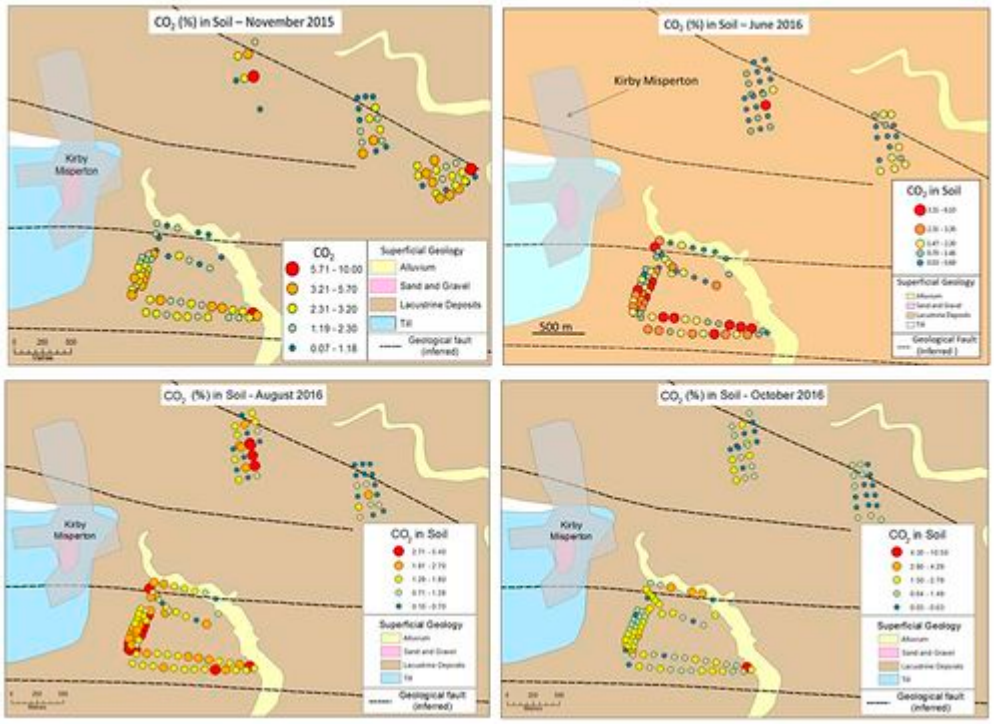



**Figure 115** Spatial plots of $CO_2$ in soil gas for the different surveys.

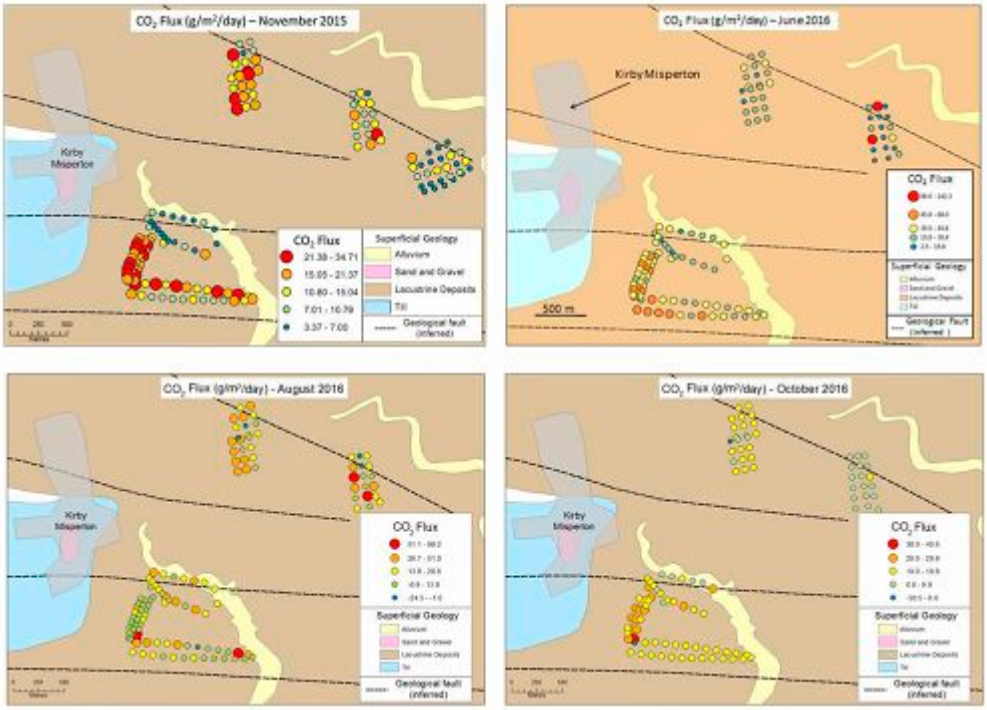



**Figure 116** Spatial plots of $CO_2$ flux from the soil for the different surveys.

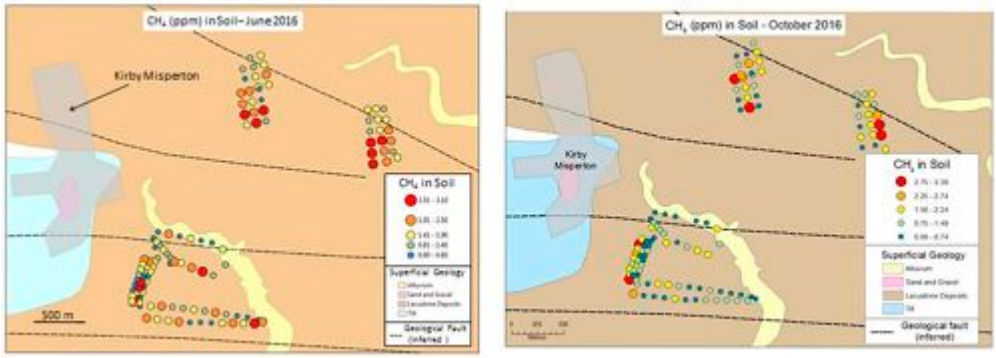



**Figure 117** Methane concentrations in soil gas for June and October 2016.

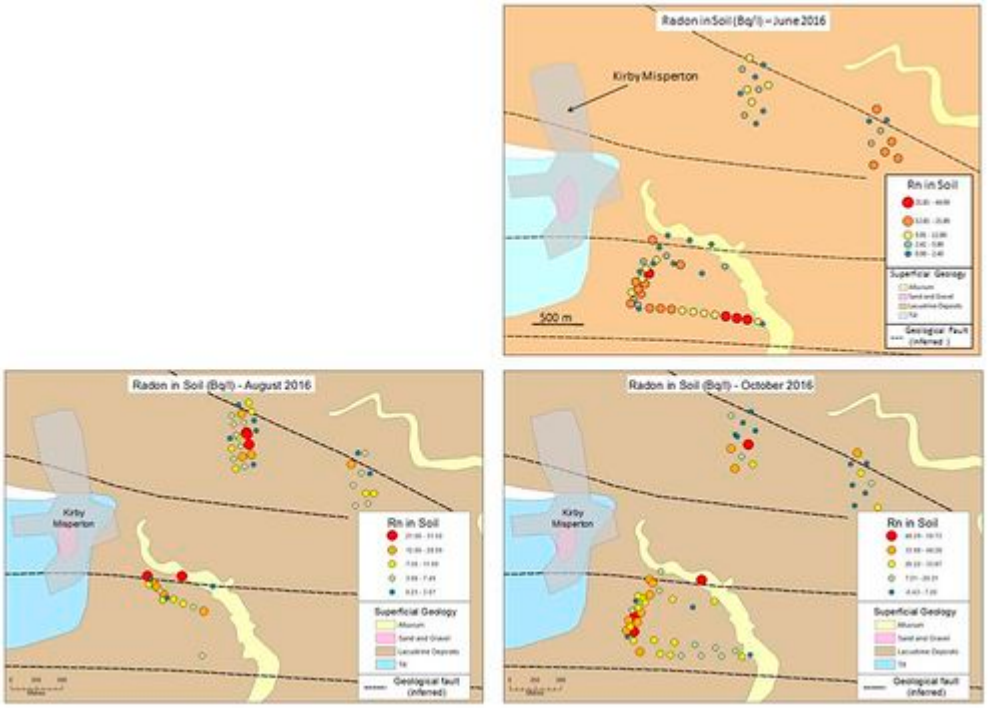



**Figure 118** Radon in soil gas for June, August and October 2016.

The mobile laser data for $CH_4$ (e.g. Figure 119) generally have a similar range of values to the soil gas with an upper limit less than twice the base atmospheric level. Higher levels in northern fields in June 2016 appeared to be related to the recent spreading of anaerobic digester slurry. The $CO_2$ laser data (e.g. Figure 120) also show a fairly restricted range within twice the global atmospheric average of around 400 ppm. Apparent spatial variability probably instead reflects diurnal changes and is likely more temporally than spatially controlled. This is suggested by gradual changes as the traverses progressed from one end of a field to the other. Seepage of gas through the soil, of geological or anthropogenic origin, is typified by relatively rapid short term changes in gas concentration over the scale of seconds to a few minutes, at particular locations, rather than such longer period variations.

Gas ratios can be a useful tool in source attribution, especially $CO_2/O_2$ and $CO_2/N_2$ plots. These have been used successfully in a number of studies related to geological $CO_2$ storage (Beaubien et al., 2013[11]; Jones et al., 2014[12]; Romanak et al., 2012[13]; Romanak et al., 2014[14]; Schroder et al., 2016[15]). An example from the Vale of Pickering is shown in Figure 121.This shows points plotting close to the ideal biogenic $CO_2$ line (where one mole of $O_2$ is consumed for every mole of $CO_2$ produced) but with scatter downwards, most likely caused by dissolution of a proportion of $CO_2$ into soil pore water. Other possible methods of source attribution include the use of stable or radiogenic carbon isotopes in $CO_2$ and $CH_4$ or noble gas isotopes. These approaches have yet to be applied to our baseline soil gas studies in the Vale of Pickering.

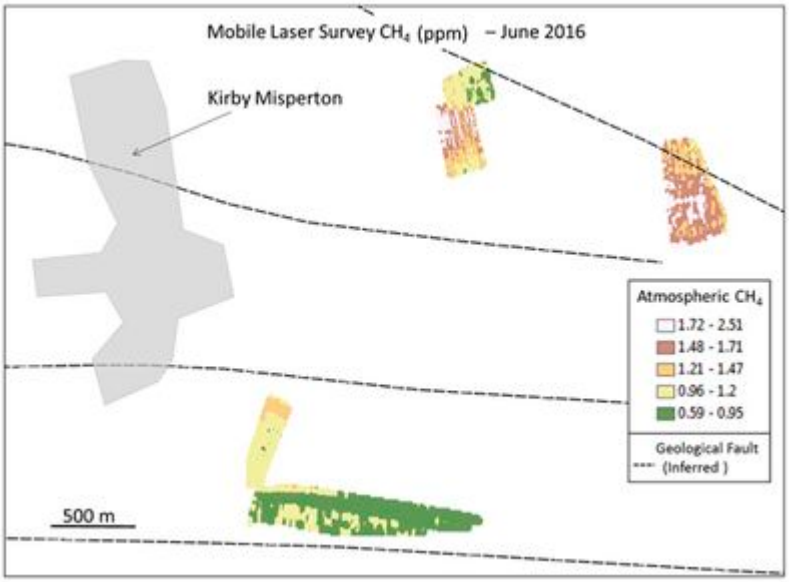



**Figure 119** An example of mobile open path laser data for $_{CH4}$ from June 2016.

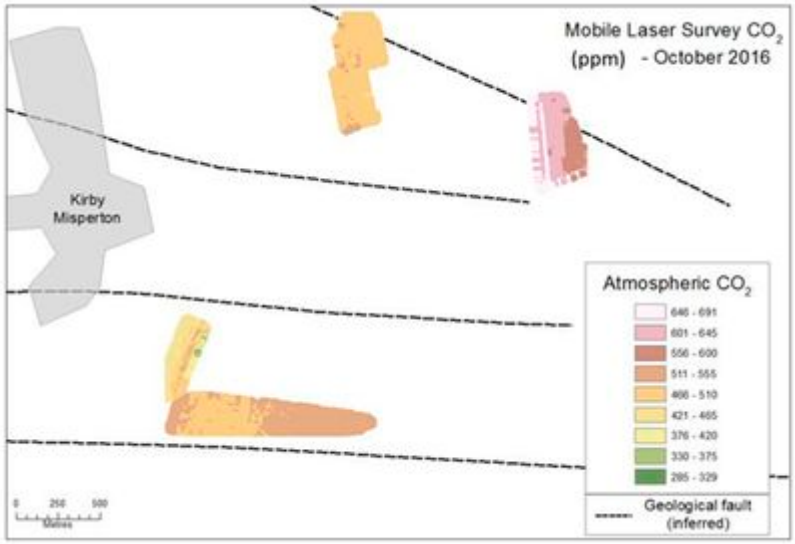



**Figure 120** An example of mobile open path laser data for CO2 from October 2016.

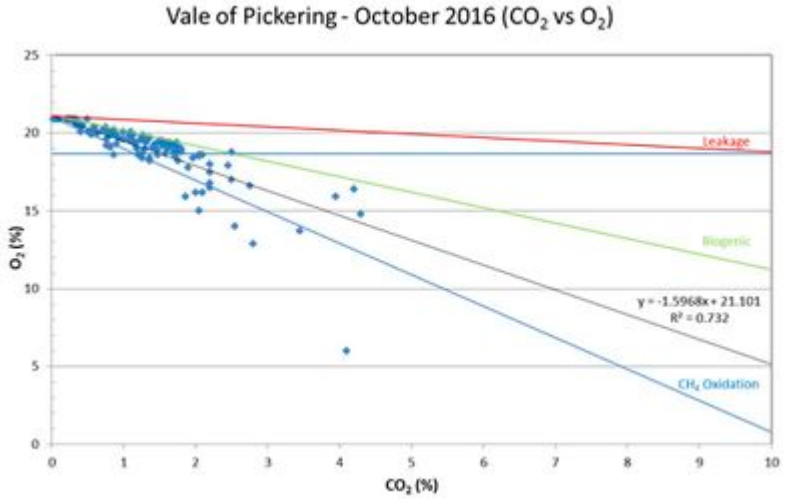



**Figure 121** $CO_2/O_2$ ratio plot for soil gas data from October 2016.

## Continuous monitoring

The $CO_2$ eddy covariance system was installed at the Preston New Road atmospheric monitoring site in January 2016 and has recorded data continuously for over a year. A soil gas monitoring station with four separate measuring probes was set up to the east of Kirby Misperton in August 2016. The failure of one probe on 4 November 2016, just after a routine site visit, caused a 1 month gap in all data. The station continued operating with 3 probes but problems occurred with a second probe on 19 January 2017. The whole station was retrieved for repair and maintenance on 3 March 2017. A four chamber automated flux system was deployed at KM8 on 14 October 2016 (Figure 122) and has operated continuously since that date with only very minor data gaps. A scanning $CH_4$ laser analyser was set up at the same location (Figure 122) at the same time and also operated from that date, but there have been data gaps. A sonic anemometer, loaned by the University of Manchester, was also installed at KM8 to assist interpretation of the laser results. Despite replacement of the original unit by the manufacturer this has not proved to be reliable and a new unit has been ordered that will interface more seamlessly with the scanning laser.

The automated flux system shows relatively low $CO_2$ fluxes, and a consistent pattern, with Chamber 4 giving the lowest values, Chambers 1 and 3 intermediate levels and Chamber 2 usually the highest fluxes (Figure 123). The range of measurements is more restricted than the survey flux results

(Figure 116). This reflects the much smaller number of sites monitored and the more sparse vegetation at KM8. The general patterns follow quite closely the variations in ground (soil) temperature, and lag slightly behind changes in the chamber (air) temperature (Figure 123). There are clear diurnal effects as well as longer period events, reflecting changing weather, and seasonal variations. For example the marked drop in flux on 22–23 February 2017 coincides with a sharp fall in atmospheric pressure from 990 to 950 hPa and reflects the passage of a low pressure weather system, probably accompanied by rainfall, that blocked the soil pores preventing the flow of gas from the soil. The fluxes were lowest in the winter months when biological activity is at a minimum and wet soil conditions may hinder gas movement from the soil.

The scanning laser system was set up to repeatedly monitor 4 separate paths, one relatively short path (path 1–about 20 m) and 3 longer paths of 70–80 m closer to, or bracketing, the KM8 wellhead and an adjacent groundwater monitoring well (Figure 122). The data (Figure 124), which are shown as 1 minute averages along the whole path length, display very similar base levels of $CH_4$ (about 1.9 ppm) to the greenhouse gas monitoring at the site (Atmospheric composition). There are significant gaps in the monitoring data, especially in the middle of the period and particularly for path 1. This is puzzling since it is the shortest path. The laser signal, for this type of instrument, can be degraded by rain, mist or condensation affecting the instrument or reflectors or the air in between. This requires further investigation and perhaps remedial measures such as instrument or reflector shrouding. Superimposed on the base $CH_4$ values are higher concentrations up to a maximum of 20 ppm, but mostly no higher than 6 ppm (Figure 124). These are rarely present on path 1, but more prevalent on paths 2–4. Similar, if slightly lower, values are seen in the greenhouse gas monitoring. These could be the result of minor gas emissions on the KM8 site, from the existing infrastructure or on-site activities, or be from more distant sources. Further analysis of the data, in conjunction with sonic anemometer measurements, would be required to resolve this.

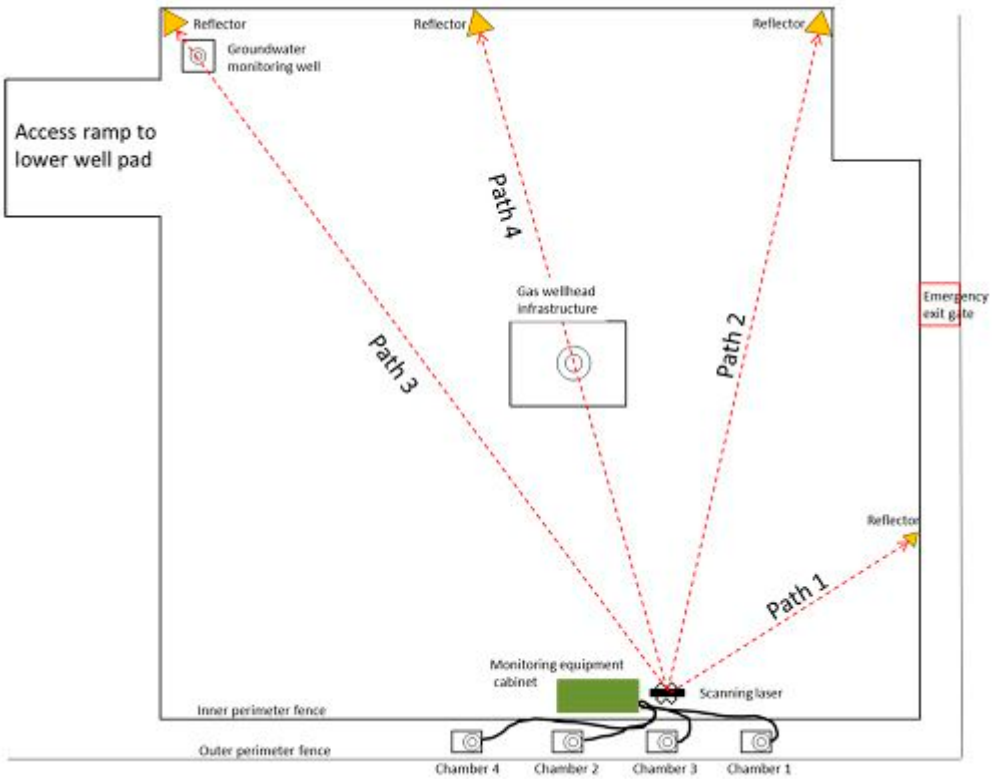



**Figure 122** Layout of automated flux chambers and scanning $CH_4$ laser at KM8.

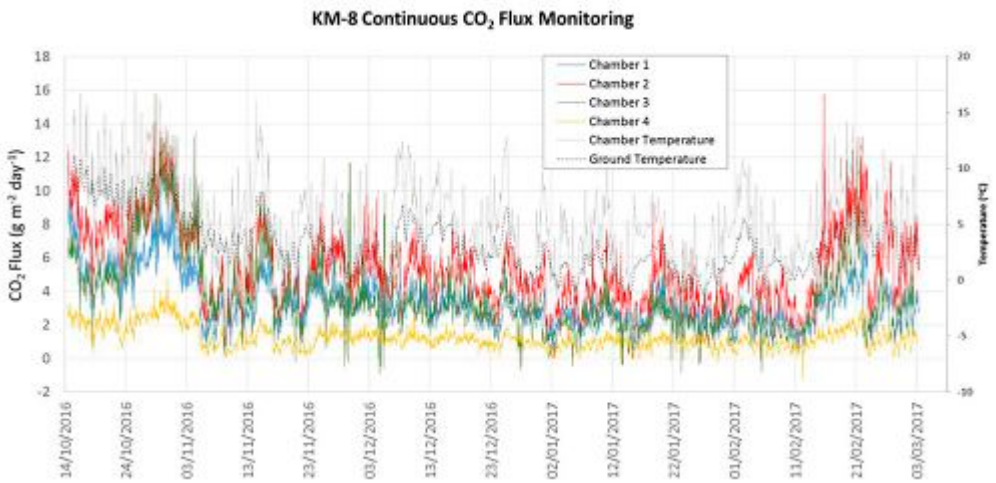



**Figure 123** Continuous flux data for the automated chambers at KM8 over a period of almost 5 months.

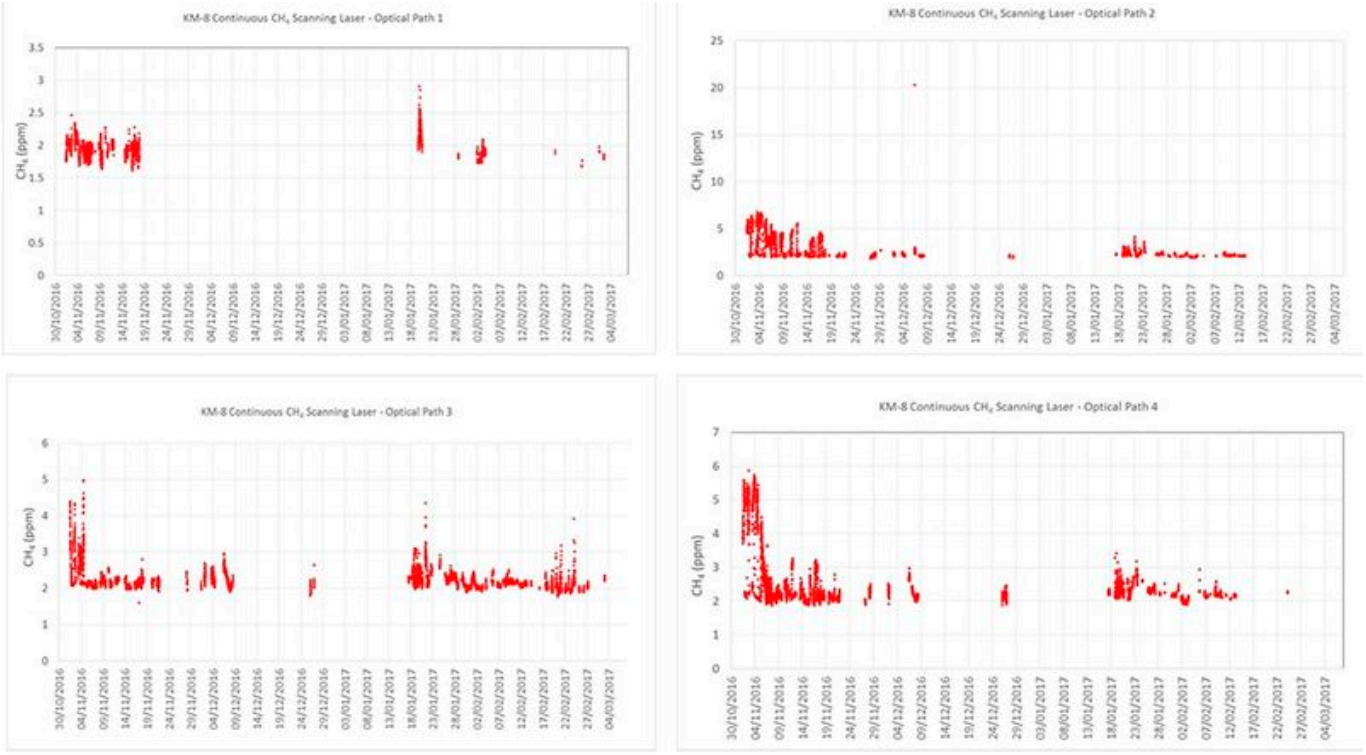



**Figure 124** Scanning $CH_4$ laser data for KM8 (see Figure 122 for paths).

The soil gas monitoring station (Figure 125) produced reliable results, usually consistent between the different probes, for the first 2 months of operation (Figure 126). After the data gap, caused by failure of probe 1, probes 2 and 3 had very similar patterns and $CO_2$ concentrations. The trends for probe 4 were similar but concentrations significantly higher. Given the subsequent failure of this probe, this might suggest instrumental (calibration) issues. Likewise the divergence between the values for probes 2 and 3 at the end of the recording period. These potential issues, and their effect on data quality should be clearer once servicing, repair and re-calibration have been completed.

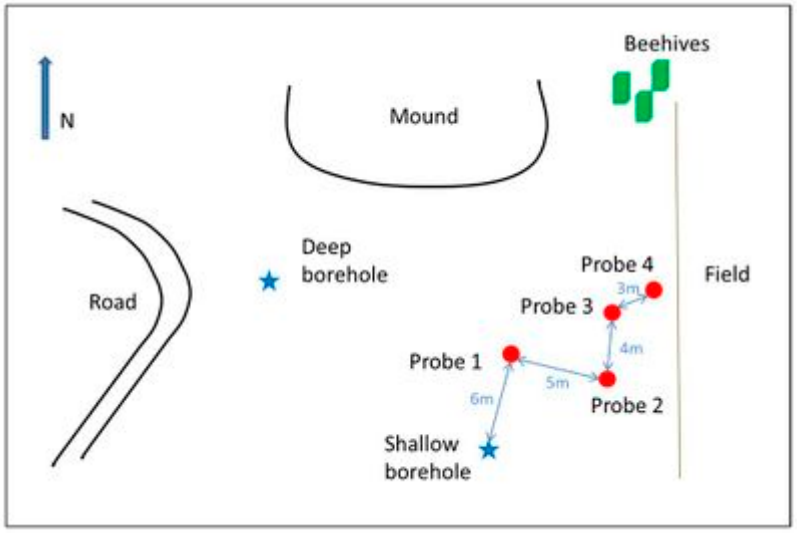



**Figure 125** Layout of soil gas monitoring station east of Kirby Misperton.

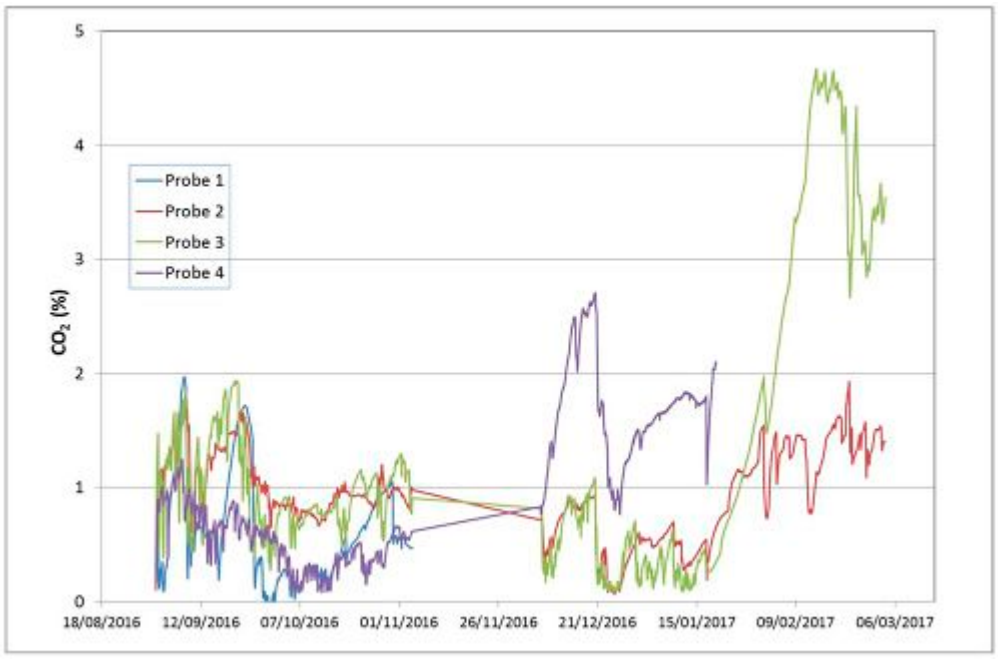



**Figure 126** Summary of all continuous soil gas data for the monitoring station east of Kirby Misperton.

## Eddy covariance

The Eddy Covariance (EC) system collects meteorological information and $CO_2$ observations. Post-processing allows $CO_2$ flux to be determined and the covariance of vertical and horizontal wind statistics and $CO_2$ flux to be calculated. The system ran continuously from the 19th Jan 2016 to present with a short down-period between 4th May 2016 and 19th May 2016.

From the data it is apparent that daily temperatures match the diurnal cycle of day and night, while over the longer annual scale seasons dictate the temperature tends (Figure 127). Due to the biological controls on natural $CO_2$ production, $CO_2$ concentration mirrors the temperature trends at both the daily and annual scales (Figure 128). Atmospheric $CO_2$ concentration ranges from 210 to over 600 ppm, however the majority of readings fall between 350 and 450 ppm. It is likely that the extreme concentration values are generated from non-local natural and anthropogenic sources, transported to the EC by the wind. Although it is not possible to distinguish natural and anthropogenic sources using the EC, the fully mixed concentration (around 370 ppm) can be considered close to the natural background for the site (see Figure 129). Using wind direction

plotted against $CO_2$ concentration there is a broad tendency for increased $CO_2$ concentrations when the wind is from the east and lower concentrations from the west (Figure 130). This is likely due to the proximity of the coast to the west of the Preston New Road study site, where there are less potential biological or anthropogenic sources and relatively clean oceanic air reaches the instrument (*see also* Atmospheric composition). As with the $CO_2$ concentration, $CO_2$ flux shows clear diurnal and annual trends consistent with natural biological processes (Figure 131). $CO_2$ flux increases during the summer months, and during this period there is also the greatest spread in flux values.

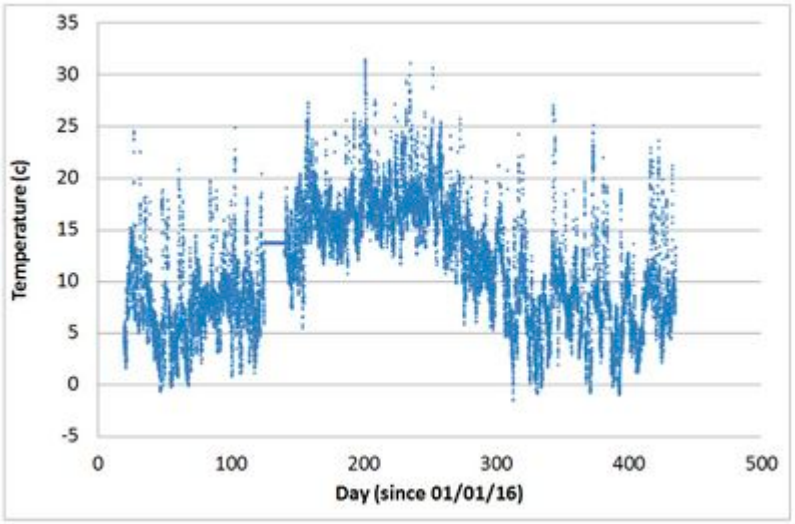



**Figure 127** Atmospheric temperature at the Preston New Road site.

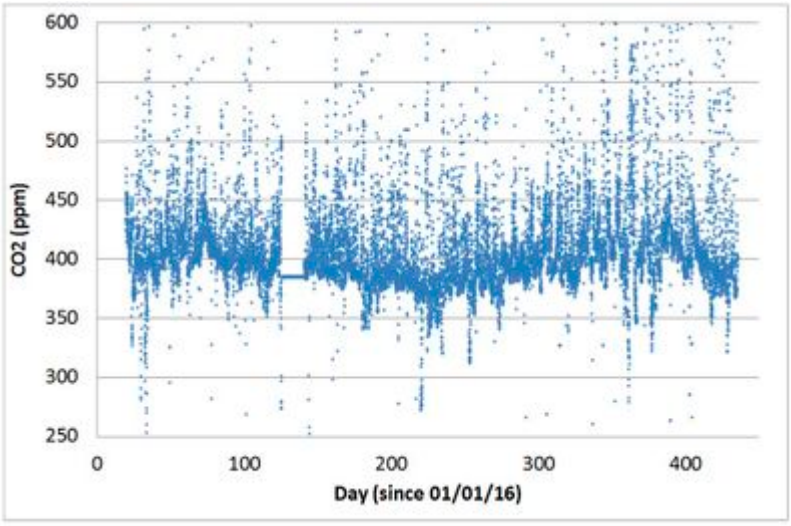



**Figure 128** $CO_2$ concentration from EC data at the Preston New Road site.

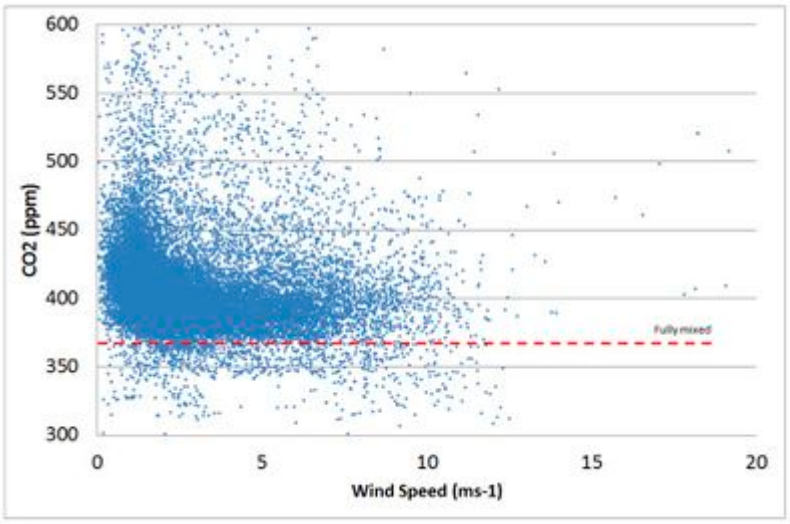



**Figure 129** Fully mixed (background) atmospheric $CO_2$ concentration at the Preston New Road site, determined by plotting $CO_2$ concentration against wind speed from EC data.

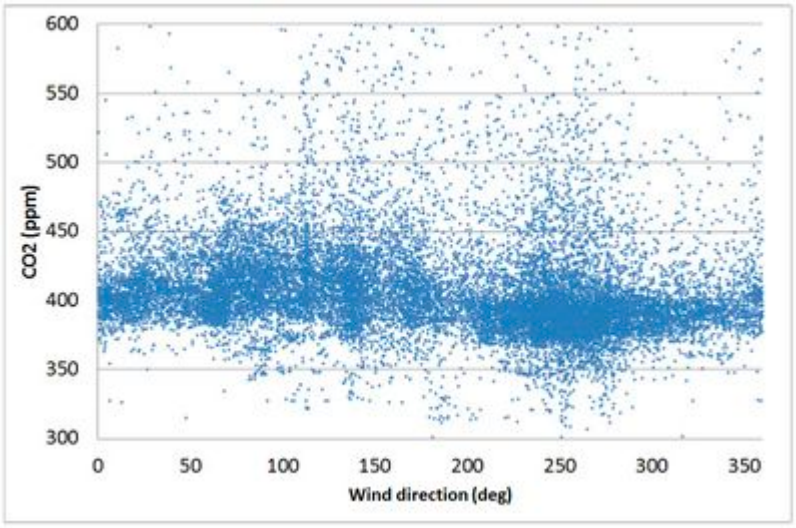



**Figure 130** Atmospheric $CO_2$ concentrations from EC data related to wind direction. Easterly winds tend to give higher concentrations while westerly winds are associated with lower concentrations.

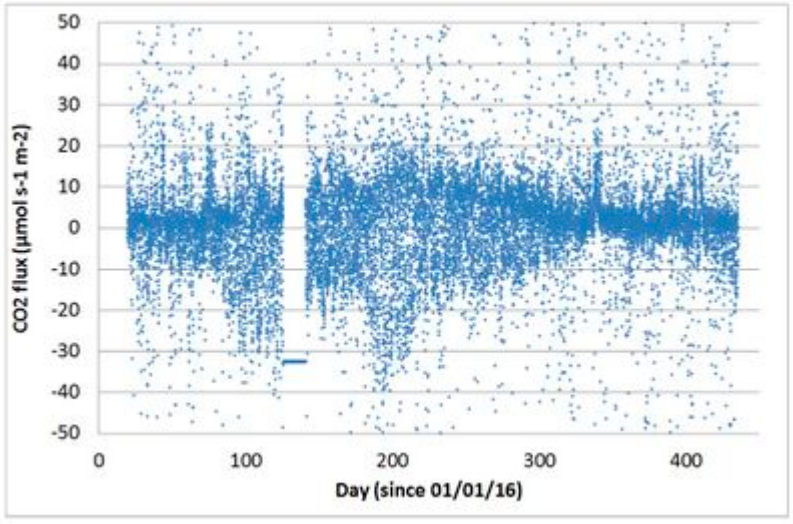



**Figure 131** Atmospheric $CO_2$ flux calculated from EC data at the Preston New Road site.

# Summary and overall conclusions on baseline monitoring and outcomes

Seasonal variability is clear in the soil gas and flux results from the Vale of Pickering, which show that meaningful data is best obtained under the relatively dry soil conditions from spring to autumn. Soil gas concentration values can be higher under wetter winter conditions making them more difficult to interpret. The optimal time for soil gas surveys during shale gas operations would be in the autumn, when biological activity (plant and microbial) is reduced but before the soil becomes saturated in the winter. In the autumn gas concentrations and fluxes are more restricted in range, making any anomalous values easier to detect. Because there is still some plant growth the effects (visually detectable or through remote sensing techniques) of any gas leakage on the vegetation should still be apparent. The lack of vegetation in harvested arable fields, or those ploughed prior to re-seeding, removes any visual clues of the impact of any gas. This is also true when there is frost or snow cover.

In the autumn surveys the $CO_2$ concentrations in the soil are mostly below 4%, with a high proportion below 2% and $CO_2$ flux is generally below 20 g $m^{-2}$ $d^{-1}$. Methane concentrations are low for all surveys, both in the soil and atmosphere, but Rn is relatively variable spatially and temporally. In the autumn it should, therefore, be possible to detect relatively small additional gas emissions through the soil, particularly for $CH_4$, although this is readily oxidised to $CO_2$ by soil microbes unless flux rates are relatively high.

Continuous monitoring data show clear diurnal and seasonal trends as well as the influence of meteorological events. A lengthier period of continuous monitoring would be desirable as there are less than 12 months of data, and significant gaps for some instruments. Deployment of a reliable sonic anemometer in conjunction with the scanning $CH_4$ laser, should allow investigation of advanced modelling and data inversion to locate the source of any emissions within the array and estimate the flux of any gas emitted.

There are some other gaps in the baseline data collected to date. For example laboratory analyses of soil gas would provide data for a broader range of gases (e.g. ethane, propane, nitrogen etc.) and higher precision results for all gases. It would also be possible to obtain improved information for source attribution, which could be further enhanced by isotope data.

Now that a reasonable body of soil gas baseline data has been collected, a fuller geostatistical analysis would be possible. This would allow optimization following the principles set out by Marchant and Lark (2007)[16] (i) to support reliable characterization of space-time mean concentrations and fluxes and their spatio-temporal variation and (ii) to allow the development of a statistical model of the variability of the measurements which can be used to support decisions on sampling requirements for operational monitoring beyond the baseline phase of the project.

# References


1. ↑ ANNUNZIATELLIS, A, BEAUBIEN, S E, BIGI, S, CIOTOLI, G, COLTELLA, M, and LOMBARDI, S. 2008. Gas migration along fault systems and through the vadose zone in the Latera caldera (central Italy): Implications for $CO_2$ geological storage. *International Journal of Greenhouse Gas Control*, Vol. 2, 353–372.
2. ↑ JOHNSON, G, HICKS, N, BOND, C E, GILFILLAN, S M V, JONES, D, KREMER, Y, LISTER, R, NKWANE, M, MAUPA, T, MUNYANGANE, P, ROBEY, K, SAUNDERS, I, PEARCE, J, SHIPTON, Z K, and HASZELDINE, R S. In press. Detection and understanding of natural $CO_2$

releases in KwaZulu-Natal, South Africa. *Energy Procedia*.
3. ↑ ZIOGOU, F, GEMENI, V, KOUKOUZAS, N, DE ANGELIS, D, LIBERTINI, S, BEAUBIEN, S E, LOMBARDI, S, WEST, J M, JONES, D G, COOMBS, P, BARLOW, T S, GWOSDZ, S, and KRÜGER, M. 2013. Potential Environmental Impacts of $CO_2$ Leakage from the Study of Natural Analogue Sites in Europe. *Energy Procedia*, Vol. 37, 3521–3528.
4. ↑ ALLISON, M L. 2001. Hutchinson, Kansas: A Geologic Detective Story. *Geotimes*, Vol. October 2001.
5. ↑ ENVIRONMENT AGENCY. 2010. Guidance on monitoring landfill gas surface emissions. *Environment Agency Report*, LFTGN 07.
6. ↑ EUROPEAN UNION. 2009a. Directive 2009/31/EC of the European Parliament and of the Council of 23 April 2009 on the geological storage of carbon dioxide and amending Council Directive 85/337/EEC, European Parliament and Council Directives 2000/60/EC, 2001/80/EC, 2004/35/EC, 2006/12/EC, 2008/1/EC and Regulation (EC) No 1013/2006 (Text with EEA relevance).
7. ↑ EUROPEAN UNION. 2009b. Directive 2009/29/EC of the European Parliament and of the Council of 23 April 2009 amending Directive 2003/87/EC so as to improve and extend the greenhouse gas emission allowance trading scheme of the Community (Text with EEA relevance).
8. ↑ SMEDLEY, P L, WARD, R S, ALLEN, G, BAPTIE, B, DARAKTCHIEVA, Z, JONES, D G, JORDAN, C J, PURVIS, R M, and CIGNA, F. 2015. Site selection strategy for environmental monitoring in connection with shale-gas exploration: Vale of Pickering, Yorkshire and Fylde, Lancashire. *British Geological Survey Open Report*, OR/15/067, pp.22.
9. ↑ FORD, J R, HUGHES, L, F, B H, and LEE, J R. 2015. The Vale of Pickering: an initial summary of the Quaternary/superficial geology and data holdings. *British Geological Survey Open Report*, OR/15/064, pp.21.
10. ↑ NEWELL, A J, WARD, R S, and FELLGETT, M, W. 2015. A 3D geological model of post-Permian aquifers and aquitards in the Vale of Pickering, North Yorkshire, UK. *British Geological Survey Open Report*, OR/15/068.
11. ↑ BEAUBIEN, S E, JONES, D G, GAL, F, BARKWITH, A K A P, BRAIBANT, G, BAUBRON, J C, CIOTOLI, G, GRAZIANI, S, LISTER, T R, LOMBARDI, S, MICHEL, K, QUATTROCCHI, F, and STRUTT, M H. 2013. Monitoring of near-surface gas geochemistry at the Weyburn, Canada, $CO_2$-EOR site, 2001–2011. *International Journal of Greenhouse Gas Control*, Vol. 16, Supplement 1, S236–S262.
12. ↑ JONES, D G, BARKWITH, A K A P, HANNIS, S, LISTER, T R, GAL, F, GRAZIANI, S, BEAUBIEN, S E, and WIDORY, D. 2014. Monitoring of near surface gas seepage from a shallow injection experiment at the $CO_2$ Field Lab, Norway. *International Journal of Greenhouse Gas Control*, Vol. 28, 300–317.
13. ↑ ROMANAK, K D, BENNETT, P C, YANG, C, and HOVORKA, S D. 2012. Process-based approach to $CO_2$ leakage detection by vadose zone gas monitoring at geologic CO2 storage sites. *Geophysical Research Letters*, Vol. 39, L15405.
14. ↑ ROMANAK, K D, WOLAVER, B, YANG, C, SHERK, G W, DALE, J, DOBECK, L M, and SPANGLER, L H. 2014. Process-based soil gas leakage assessment at the Kerr Farm: Comparison of results to leakage proxies at ZERT and Mt. Etna. *International Journal of Greenhouse Gas Control*, Vol. 30, 42–57.
15. ↑ SCHRODER, I F, ZHANG, H, ZHANG, C, and FEITZ, A J. 2016. The role of soil flux and soil gas monitoring in the characterisation of a CO2 surface leak: A case study in Qinghai, China. *International Journal of Greenhouse Gas Control*, Vol. 54, Part 1, 84–95.
16. ↑ Marchant, B P, and Lark, R M. 2007. Optimized sampling schemes for geostatistical surveys. *Mathematical Geology*, **39**, 113–134.

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