Ground Gas Information Sheets

Using ternary plots for interpretation of ground gas monitoring results
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Using ternary plots for interpretation of ground gas monitoring results

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Ternary plots are commonly used to allow interpretation of ground gas monitoring results. There are various ways of plotting data in ternary graphs. This paper explains two different approaches that can be used and the implications that need to be considered when interpreting the data. It also provides advice on using ternary plots to help characterise the ground gas regime and risk where only low concentrations of carbon dioxide and/or methane have been recorded in monitoring wells without elevated flow rates.

Introduction

Ternary plots are commonly used to plot ground gas monitoring results (Teasdale et al 2014 and 2015). They are also used to assess the flammability of methane and air mixtures (Figure 1) and to assess geological and hydrogeological data.

A ternary plot is a triangular plot of three variables which must sum to a constant value, e.g. 1.0 or 100% (Howarth, 2009). In most cases the ratios of the three variables are plotted as points on an equilateral triangle (West, 1982).

There are two ways of plotting data in ternary graphs. This paper explains each of the approaches that are used and the implications that need to be considered when interpreting the data.

Ternary plots allow trends in gas composition to be identified and this can help to identify the potential source of the ground gas. It should not be used in isolation of other data nor without a robust conceptual site model.

BS8485: 2015 and previous assessment methods (Wilson and Card, 1999, Boyle and Witherington, 2007 and Wilson et al, 2007) require that where the carbon dioxide concentration exceeds 5% consideration is given to increasing a site classification from Characteristic Situation 1 up to Characteristic Situation 2. Carbon dioxide is widely present in natural soils at concentrations

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up to 21% and this often leads to uncertainty about whether to increase the classification. A ternary plot can help to assess gas monitoring data to identify if there is an elevated risk and whether the classification should be increased.

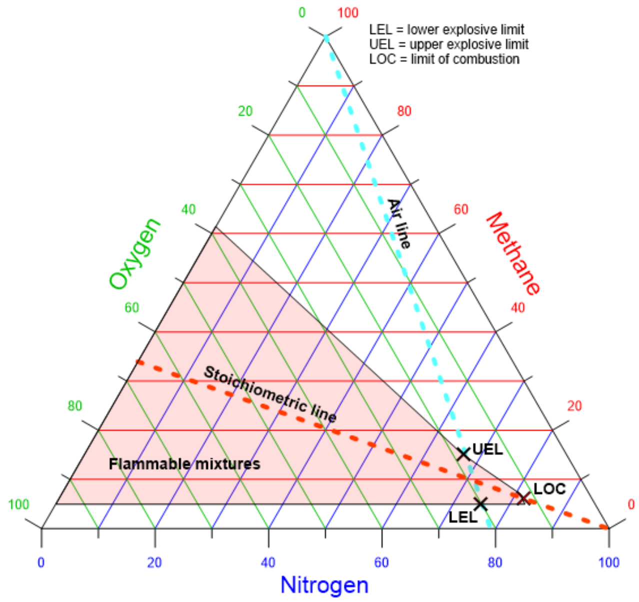


Figure 1 Flammability diagram for methane

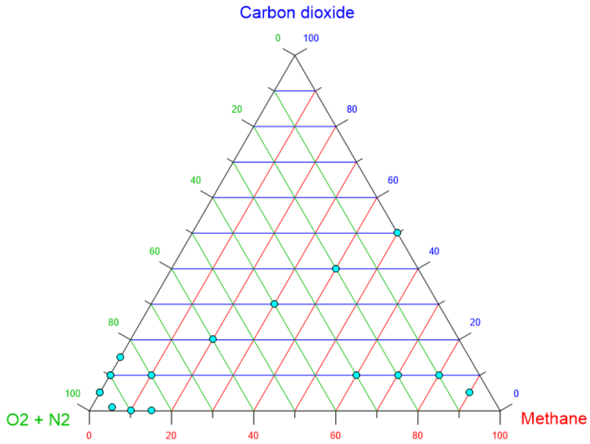
How to read a ternary plot

There are different ways of plotting the axis labels on ternary plots. These are:

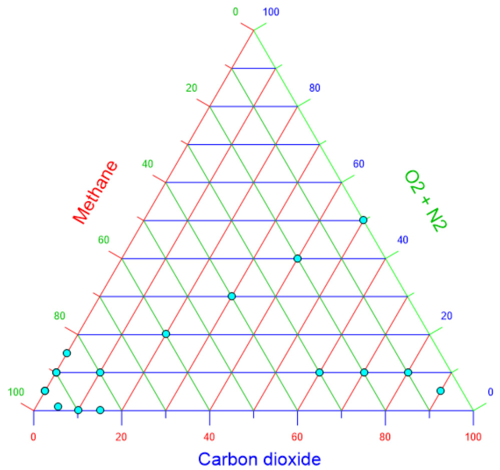
1. place the axis label at the apex of the triangle at the point where the axis value is 100 (Figure 2a).
2. place the label alongside the axis zero line (Figure 2b). This can be confusing at first glance because the labels are not alongside the axis values.
3. place the label alongside the axis values (Figure 2c).

Whichever approach is taken it is useful to colour the axis labels, values and the gridlines so it is clear which axis relates to which gridlines. This makes it much easier for users to read the data from the graph.

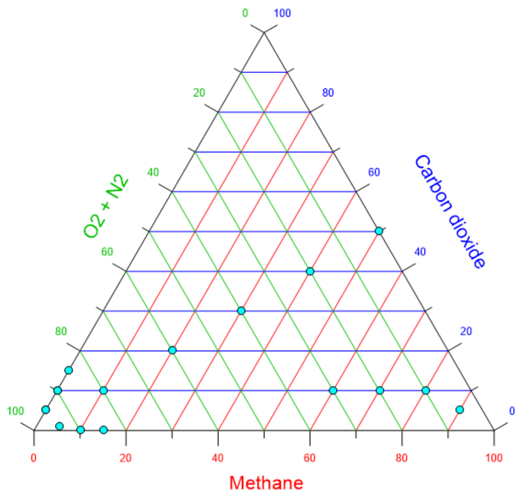
An example of how to read the data from a graph is shown in Figure 3.



(a) label at apex



(b) label alongside zero line



(c) Label alongside axis values

Figure 2 Different methods of axes labelling for ternary plots

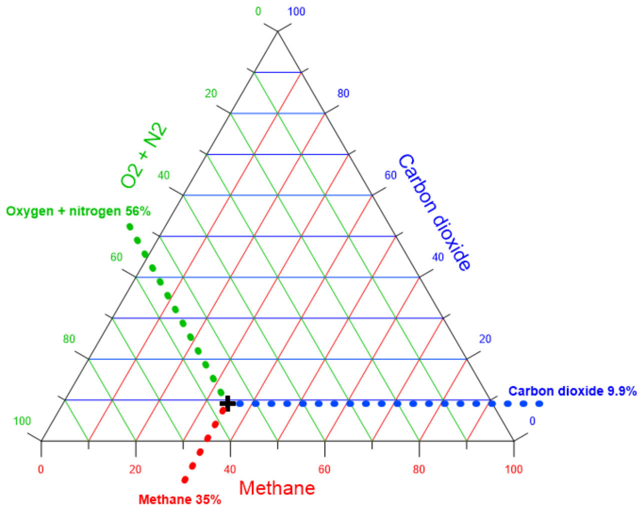


Figure 3 Reading data from a ternary plot

Plotting data on a ternary plot

As discussed in the introduction the three variables being plotted on a ternary diagram must sum to a constant value. For ground or landfill gas assessment when considering the permanent gases methane, carbon dioxide, oxygen and nitrogen, this is normally 100%. The contribution from any trace gases at ppm level is ignored (e.g. hydrogen sulphide or carbon monoxide). However, these trace components should be considered separately as they can give useful information regarding the source of the main permanent gases.

There are two ways to plot the data to achieve the requirement that all the values add to a constant value:

1. Plot methane, carbon dioxide and oxygen + nitrogen;
2. Plot the relative proportion of each gas (methane, carbon dioxide and oxygen) compared to the sum of all three gases, ignoring the presence of nitrogen.

Teasdale et al (2014) state the data plotted were "normalised" values of methane, carbon dioxide and oxygen (e.g. CH_4:N_2). However simply dividing each gas by N_2 is not consistent with ternary plots because the sum for all the gases (CH_4:N_2 + CO_2:N_2 + O_2:N_2) does not add up to a constant for all sets of results, as discussed below.

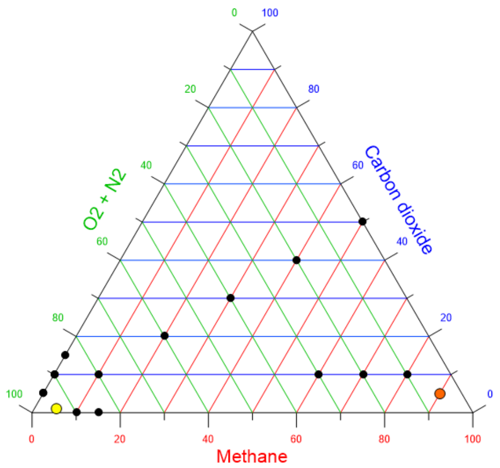
The approach adopted by the same authors later (Teasdale et al, 2015) used Method 2 from the list above, rather than normalising the data by simply dividing each result by the nitrogen content, ie the plots are showing the relative proportion of each gas in relation to the sum of the three main gases (CH_4 + CO_2 + O_2).

Using Method 1 (plotting methane, carbon dioxide and oxygen + nitrogen) ensures the basic requirement of the ternary plot is achieved, ie the values sum to the same constant. It is easy to read the values from the graph and any relationships shown on the plot will be the same for any gas concentrations from different data sets. The data set in Table 1 has been plotted in this way in Figure 4a.

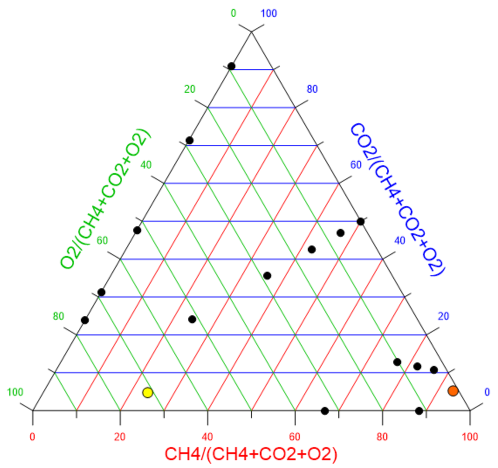
Table 1 Data set for ternary plot in Figure 4a

Methane (%)	Carbon dioxide (%)	Oxygen (%)	Nitrogen (%)	Nitrogen + oxygen (%)	SUM (%)
10.0	10.0	21.3	58.7	80.0	100.0
20.0	20.0	15.9	44.1	60.0	100.0
30.0	30.0	10.6	29.4	40.0	100.0
40.0	40.0	5.3	14.7	20.0	100.0
49.9	50.0	0.0	0.1	0.1	100.0
60.0	10.0	8.0	22.0	30.0	100.0
70.0	10.0	5.3	14.7	20.0	100.0
80.0	10.0	2.7	7.3	10.0	100.0
90.0	5.0	1.3	3.7	5.0	100.0
5.0	1.0	15.0	79.0	94.0	100.0
10.0	0.0	5.0	85.0	90.0	100.0
15.0	0.0	2.0	83.0	85.0	100.0
0.0	5.0	16.0	79.0	95.0	100.0
0.0	10.0	11.0	79.0	90.0	100.0
0.0	15.0	6.0	79.0	85.0	100.0
0.0	5.0	11.0	84.0	95.0	100.0
0.0	10.0	1.0	89.0	90.0	100.0

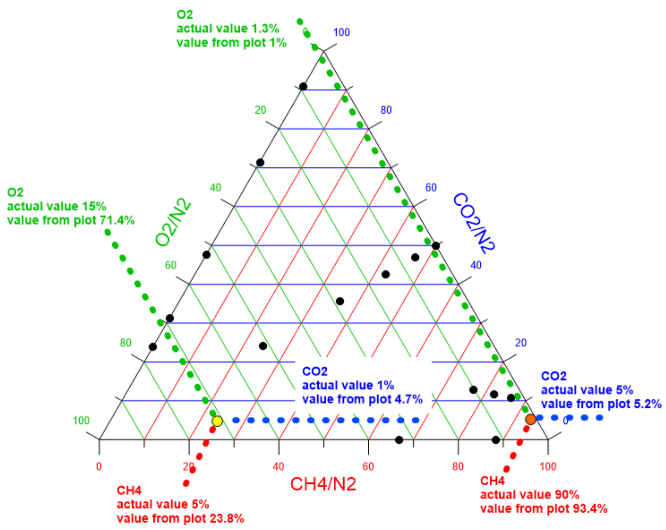
This approach is useful where the detected gas is essentially air with low concentrations of carbon dioxide and/or methane, such as encountered on many contaminated land sites or in natural soils. For Method 2 the data from Table 1 has been adjusted to give the relative proportions of each gas (Table 2 and Figure 4b).



(a) plot with oxygen + nitrogen (Table 1)



(b) plot of relative proportions (Table 2)



(c) plot of "normalised" data (Table 3)

Figure 4 Ternary plots for data in Tables 1, 2 and 3

Comparison of the orange and yellow shaded rows from Tables 1 and 2 shows that where methane and/or carbon dioxide results are high there is little difference between the plotted values and actual results for Method 2. However, where methane and carbon dioxide concentrations are low there is a large difference between values on the graph and actual results.

The data from Table 1 has also been normalised by dividing each gas by the nitrogen concentration and the results are provided in Table 3 and plotted in Figure 4c.

Table 2 Relative proportion of each gas to sum of CH_4, CO_2 and O_2 (date for plot in Figure 4b)

CH4/(CH4 + CO2 + O2)	CO2/(CH4 + CO2 + O2)	O2/(CH4 + CO2 + O2)	SUM
24.23313	24.23313	51.53374	100
35.74661	35.74661	28.50679	100
42.47312	42.47312	15.05376	100
46.88427	46.88427	6.231454	100
49.94995	50.05005	0	100
76.94805	12.82468	10.22727	100
82.04748	11.72107	6.231454	100
86.3388	10.79235	2.868852	100
93.4297	5.190539	1.379763	100
23.80952	4.761905	71.42857	100
66.66667	0	33.33333	100
88.23529	0	11.76471	100
0	23.80952	76.19048	100
0	47.61905	52.38095	100
0	71.42857	28.57143	100
0	31.25	68.75	100
0	90.90909	9.090909	100

This shows that the sum of the three normalised values is different for each data set. This does not comply with the basic requirement for a ternary plot, ie that all components sum to a constant value.

To deal with this the software used to plot the graph must recalculate the three components to sum to 100%, which obviously affects the composition data shown on the graph. There is no alternative to this, because the three values must intersect in one point, and this will not happen if these do not sum to 100% (or other constant value).

Table 3 Normalised data (dividing by N_2) (data for plot in Figure 4c)

CH4/N2	CO2/N2	O2/N2	SUM
0.17	0.17	0.36	0.70
0.45	0.45	0.36	1.27
1.02	1.02	0.36	2.41
2.72	2.72	0.36	5.81
499.00	500.00	0.00	999.00
2.72	0.45	0.36	3.54
4.77	0.68	0.36	5.81
10.90	1.36	0.36	12.62
24.52	1.36	0.36	26.24
0.06	0.01	0.19	0.27
0.12	0.00	0.06	0.18
0.18	0.00	0.02	0.20
0.00	0.06	0.20	0.27
0.00	0.13	0.14	0.27
0.00	0.19	0.08	0.27
0.00	0.06	0.13	0.19
0.00	0.11	0.01	0.12

Orange shading is data for sample orange point in Figure 5

What this in effect then shows is the relative proportion of methane, carbon dioxide and oxygen in each sample as seen in the plots in Figure 4b and 4c which show the same distribution of points for the "normalised" data as for the relative proportions determined by Method 2 described earlier in this paper (from Table 2).

With such a plot it is difficult to understand the relationships between the original data points.

Sample data points from Table 3 are shown in orange and yellow on the plot in 4(c). This shows that the values read from the graph do not represent the actual values on Table 3, nor the actual monitoring results in Table 1. As discussed earlier, the lower the methane and carbon dioxide concentrations the more pronounced this effect.

Therefore, the plot does not represent "normalised" data with respect to nitrogen. It represents the relative proportions of each gas, excluding nitrogen.

Regardless of which approach is used, both can give useful insights into the source of gas. Teasdale et al (2015) provided a series of plots in which different zones on the ternary plot indicated gas from different sources. Examples included distinguishing between landfill gas migration and gas from Coal Measures (Figure 5).

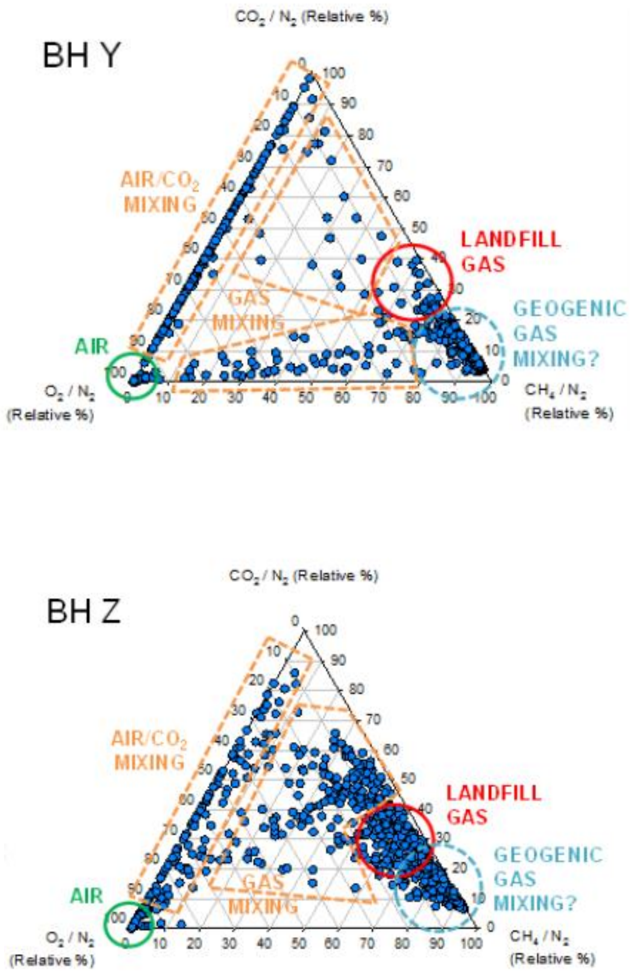


Figure 5 Gas composition from different sources (Teasdale et al 2015)

Application of ternary plots to risk assessment

Carbon dioxide is widespread in the sub surface environment and is generated by microbial and geochemical processes. If there is any organic, carbonate or pyrite content to the soils or rocks then carbon dioxide could potentially be present at concentrations up to 21% v/v. Soils in the UK where carbon dioxide is commonly encountered at elevated concentrations include Glacial Till, Chalk, River Terrace Gravel, Thanet Sand, Lambeth Group and Made Ground.

When monitoring wells are installed in these materials, the small volumes of organic material are exposed to oxygen. This can result in biological respiration or oxidation of the material resulting in the production of carbon dioxide. Weathering of pyrites and the resultant reactions of acidic pore water with carbonate material can also cause increased concentrations of carbon dioxide in the monitoring well headspace.

Low volumes of organic material in Made Ground can also degrade aerobically to produce carbon dioxide, or may locally be degrading anaerobically with the process being so slow that the methane completely oxides to carbon dioxide before reaching the well headspace. In all these cases the carbon dioxide is generated so slowly that it will not be emitted from the ground surface in quantities or at a rate that is sufficient to pose a risk to overlying development.

However, there are situations where carbon dioxide could pose a risk and elevated concentrations require careful consideration:

- Landfill gas migration through open fractured rock or other highly permeable pathway;
- Old open coal mine workings that have a free connection to the ground surface;
- High flow of acidic mine water in open working or fractured rock with an open pathway to the surface;
- Volcanic activity causing emission of gas from the ground.

For this reason, all of the commonly used screening approaches used in the UK (BS8485: 2015, Wilson and Card, 1999, CIRIA Report C665 – Wilson et al, 2007, and NHBC - Boyle and Witherington, 2007) have a requirement to consider increasing the characterisation of a site identified as Characteristic Situation CS1 or Green based on the Gas Screening Value, if carbon dioxide concentrations exceeding 5% have been recorded.

This increase in characterisation is not a mandatory requirement in any of the guidance documents. The distribution of elevated concentrations and the source of the gas should be considered before deciding whether the increase is appropriate. In most cases there will not be any need to increase the classification if the carbon dioxide is caused by biological respiration of small quantities of organic material. Increasing the characteristic situation is only likely to be a requirement if the gas source is one of the four high risk sources identified above. Note that unworked Coal Measures can result in high carbon dioxide or methane concentrations and low oxygen concentrations in monitoring wells and are not considered high risk (only open workings connected to the surface are high risk).

When aerobic biological respiration oxidises organic material, it does so as follows:

$$CH_2O + O_2 \rightarrow CO_2 + H_2O \qquad (1)$$

This means that as oxygen is consumed and the oxygen concentration reduces, the carbon dioxide concentration increases in the same proportion. The zone this trend occupies is shown on the ternary plot in Figure 7. Note that the plot has an oxygen + nitrogen axis to define the zone.

There may also be trace amounts of methane up to about 3% caused by anaerobic decomposition in small anaerobic hotspots or the reduction of carbon dioxide by methanogens. Oxygen concentrations may be depleted but in this scenario oxygen deficient air is not likely to be emitted quickly from the ground and it does not pose a risk.

Also plotted is the line showing potential landfill gas migration that is displacing air from the ground (red dotted line). This is based on a mix of 60% methane and 40% carbon dioxide at source with no chemical changes or oxidation of methane to change the CH_4:CO_2 ratio of the composition as it migrates and displaces atmospheric air (which may be true within a few meters of the source or at the centre of a large plume but is unlikely at greater distances or at the edge of large plumes)

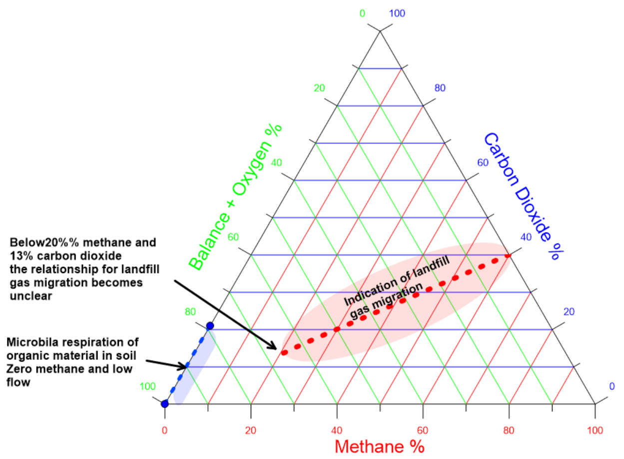


Figure 6 Ternary plot showing aerobic soil respiration zone and landfill gas migration zone

Examples

The gas monitoring data from three example sites is provided in Table 4, together with a summary of the ground conditions. These results are presented as ternary plots in Figures 7 to 9.

These sites have low carbon dioxide and methane concentrations from aerobic respiration of small quantities of organic material in the soil.

In all cases it was shown that the rate of gas generation via the respiration process in the natural soils or Made Ground was very low (ie a low risk or very low risk source in accordance with BS8576: 2013).

Therefore, where gas monitoring results plot in the zone shown in Figure 6 for microbial respiration there is no requirement to increase the characteristic situation simply because the carbon dioxide concentration exceeds 5% (this should be supported by other data such as understanding the source composition and a comprehensive site conceptual model).

At Site 2 underfloor void monitoring confirmed that gas emissions into the void were not significant (less than 0.04% methane and less than 0.01% carbon dioxide) and were well below levels that would pose a risk to the development. Therefore the single elevated methane result that was outside the zone of microbial respiration was not considered significant and did not warrant an increase to CS2.

Table 4 Summary of details for example sites

Source of gas	Methane (%)	Carbon dioxide (%)	Oxygen (%)	Flow (l/h)
Site 1				
River Terrace Deposits generally comprising gravelly SAND or sandy GRAVEL, with varied quantities of silt.	<0.1	0.1 – 7.2	11.2 – 21.2	0.1 – 0.3
Site 2				
Made Ground comprising red brown slightly silty slightly gravely clay with gravel of quartzite, siltstone, sandstone, burnt shale, flint, fragments of timber, brick slag and clinker. At the base of the Made Ground was a layer of old topsoil or soft grey black slightly gravelly organic clay with sandstone, burnt shale and fragments of black plant remains	<0.1 – 9.6	6.6 - 13.4	0.3 – 15.2	0.1 – 0.8
Site 3				
Glacial Deposits comprising loose to medium dense fine to coarse sand with variable amounts of silt and clay. Occasionally comprises stiff reddish brown sandy clay in places	0.1 – 0.2	0.1 – 9.2	9.3 – 21.3	0.1

Conclusions

Plotting gas monitoring data using ternary plots is commonly used as a tool in gas risk assessment. There are different ways of presenting the plots. Using coloured axes and labels helps users interpret data on the plots.

To interpret trends from site to site the data sets must sum to a constant and normalising by simply dividing by the nitrogen concentration prevents such comparisons being made easily. Two methods are used to present data on ternary plots: either as a plot of methane, carbon dioxide and oxygen + nitrogen or as a plot of the relative proportions of each gas, excluding nitrogen.

Using either method allows trends in data to be identified and potential sources of gas differentiated.

It is common in natural soils and low generation potential Made Ground for concentrations of carbon dioxide above 5% to be present, but for the Gas Screening Value (GSV) to indicate Characteristic Situation CS1. Ternary plots can be used to identify when concentrations above 5% caused by microbial respiration of carbon dioxide or similar low risk processes do not require an increase from Characteristic Situation CS1 to CS2.

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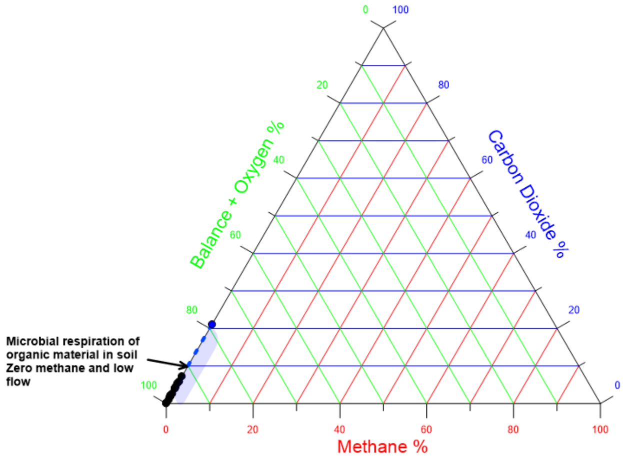

Figure 7 Ternary plot for Site 1

0.1 -

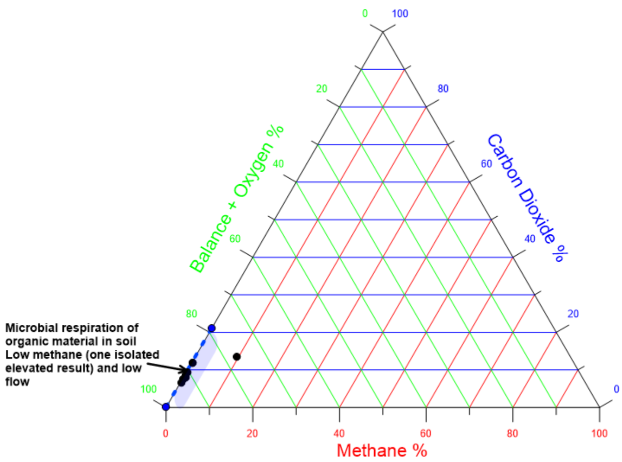

Figure 8 Ternary plot for Site 2

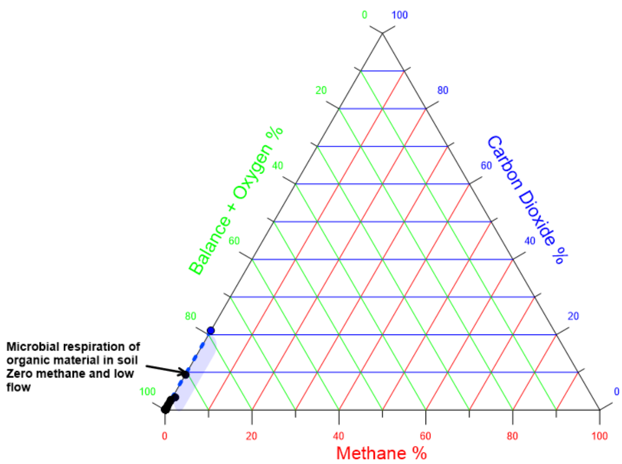

Figure 9 Ternary plot for Site 3

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